Flandrian sea-level changes and impacts of projected sea-level rise on the coastal lowlands of Morecambe Bay and the Thames Estuary, U.K.

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FLANDRIAN SEA-LEVEL CHANGES AND IMPACTS OF PROJECTED SEA-LEVEL RISE ON THE COASTAL LOWLANDS OF MORECAMBE BAY AND THE THAMES ESTUARY, U.K.

VOLUME ONE
Main Text, References and Tables

by

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A Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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February 1993

英国摩肯比海湾及泰晤士河口全新世海平面变化与未来海面上升对这些海岸地区的影响

博士毕业论文

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FLANDRIAN SEA-LEVEL CHANGES AND IMPACTS OF PROJECTED SEA-LEVEL RISE ON THE COASTAL LOWLANDS OF MORECAMBE BAY AND THE THAMES ESTUARY, U.K.

Abstract

This thesis aims to reconstruct the Flandrian sea-level history of Morecambe Bay, from which, comparisons are made with the contrasting area - the Thames Estuary. This thesis also aims to assess the likely impacts of projected sea-level rise on the two coastal areas in the next century.

A detailed investigation of Flandrian stratigraphy has been carried out in the area of Skelwith Pool, north of Morecambe Bay, by applying stratigraphic survey and pollen and diatom analyses. The results suggest that a rapid rise in sea level during 8300-7000 B.P. was followed by a rising and fluctuating sea-level during 7000-3500 B.P. The fluctuating sea-level resulted in alternative clastic and organic deposition. Regional and local isostatic components and palaeo-tidal variation are analyzed. The relationship between movements in sea level and changes in deposition are also explored.

Attention is drawn to the uncertainties of the published sea-level scenarios. Two of the scenarios are adopted. Natural responses of coastal hydrology and sedimentation to the rising sea-level are explored. Effectiveness of the existing sea defence is assessed. Geographical Information Systems for the two coastal areas are established and the coastal lowlands subject to marine inundation are identified in terms of their altitudes and nature of landuse. Three pilot areas of different types of landuse and topography - Skelwith Pool, Heysham and Morecambe, and Canvey Island - are selected and impacts of sea-level rise in these areas are listed.

Acknowledgements

As this work would not have been achieved without support from the following organisations, I would express my acknowledgement to them. They are Darchem Ltd. U.K., the Committee of Vice Chancellors and Principals of the Universities of the U.K., the British China Education Trust, British China Centre, and the Dean of the Colleges and St. Aidan's College, University of Durham.

To Dr. M.J. Tooley who has supervised this work throughout, I give my deepest gratitude for his advice, encouragement and comments on this work, and also for his kindnesses in helping my family in many ways.

My acknowledgement should also give to all of my colleagues, Mr. G. Englefield, Miss A. Hinton, Dr. I. Shennan, Dr. A. Long, Mr. D. Bedlington, Dr. A. Plater, Mr. I. Sproxton, Dr. J. Innes, Mr. F. Bell, and Mr. D. Coates, for their assistance, fruitful discussions and suggestions. I should also thank Professor K. Platt, Mr. T. Mar, Dr. M. Green, Mrs. D. Green, Mrs. Roberts and Mr. J. Pedley for their help.

I should express my special acknowledgement to Professor Yuanbo Liang, Professor Zhenguo Huang, and Professor Pingri Li, who have kindly guided and encouraged me walking through the academic gateway and climbing up the scientific ivorytower. I also thank the colleagues in the Guangzhou Institute of Geography for their support.

Finally, I give my sincere acknowledgement to my wife and my parents for their moral support.

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CHAPTER I

INTRODUCTION

In this chapter, the aims, scope, significance and hypothesis of the thesis are explained. The methodology employed and the sites investigated are introduced. For these purposes, the chapter is structured into the following four sections.

1.1. Aims and scope of the thesis

1.2. Methodology

1.3. Significance and hypothesis of the study

1.4. The sites investigated

1.1. Aims and Scope of the Thesis

This thesis has two major aims which are:

1. to reconstruct the Flandrian sea-level history in Morecambe Bay, and compare it with a contrasting area, the Thames Estuary, from which, relations between changes in sea level, changes in coastal sedimentation and movements of

coastlines can be derived;

2. to identify the likely impacts of sea-level change in the next century on the two areas, a predominantly rural area (Morecambe Bay) and a predominantly urban and industrial area (the Thames Estuary). This study will concentrate on the natural and physical adverse effects which should include the responses of marine hydrology, coastal sedimentation and coastlines, and marine flooding upon the reclaimed lands.

In order to approach the first aim, a detailed investigation of Flandrian stratigraphy has been carried out in the area of Skelwith Pool, the catchment adjacent to the Leven estuary, on the north side of Morecambe Bay, by applying various techniques such as stratigraphic survey, pollen and diatom analyses and radiocarbon dating. In addition, the Flandrian sea-level history has been reconstructed by employing methods of interpretation of sea-level index points derived from the stratigraphic studies. During the reconstruction of the sea-level history, geological components of glacio-isostatic uplift or subsidence have been considered by comparison with the sea-level data in the Skelwith Pool catchment with its counterparts in and around Morecambe Bay, as well as those in the Forth valley, north-east Scotland where uplift during the Flandrian Age has happened and those in south-east England, the Thames

Estuary in particular, where subsidence during the Flandrian Age has occurred.

In order to achieve the second aim, this study has been carried out by applying: (1) the theory of the "Greenhouse Effect" which includes global warming and the consequences for sea level, (2) the experience of coastal responses to the Flandrian sea-level changes which is derived from the studies of Flandrian stratigraphy, (3) knowledge of contemporary processes of coastal hydrological parameters, sedimentation and coastlines, and (4) the technique of Geographical Information Systems which provides possibilities to identify the likely impacts of future sea-level rise on the two coastal lowlands and produce a spatial resolution. The assessment of the likely impacts of projected sea-level rise in the next century has been focused on two coastal lowlands, one in Morecambe Bay and the other along the Thames Estuary. The coastal lowlands here are defined as the area which was mainly built up by Quaternary sediments, is lowlying at present below extreme high water levels, and would be affected by the future rising sea-level. For a further detailed assessment, three small pilot areas are selected. They are: 1. Skelwith Pool and the south part of Roudsea Wood, for their ecological importance; 2. Heysham and Morecambe, for the importance of the nuclear power station and the holiday resort; 3. Canvey Island and its adjacent lowlands, for their dense residential populations and large petroleum refineries which are at high risk from marine flooding if particular sea-level rise scenarios are realised.

In short, the present work comprises two parts: a study of Flandrian sea-level history of the Morecambe Bay area, and a study of the impacts of relative sea-level change in Morecambe Bay and the Thames Estuary. The scope and framework of the thesis can therefore be illustrated in Figure 1.1. Of which, information of Flandrian eustasy and isostasy, hydrological and sedimentary data, records of local resident's activities, and sea-level scenarios are critically referred from other researchers.

The processes and results of the study are demonstrated by ten chapters in this thesis. Beside the introduction in this chapter, Chapter II reviews the published literature and summarises the basic theory of sea-level changes, methods of reconstructing the sea-level history, terminology in sea-level research, major results in sea-level studies and the theory of the greenhouse effect. Chapter III introduces the techniques employed. Chapter IV and V illustrate the stratigraphic survey carried out, examine the available sea-level index points collected and reconstruct the Flandrian history of sea-level changes, with consideration of regional and local isostatic factors and with an assessment of the relations between changes in sea level and evolution in the coastal area. Chapter VI discusses the likely rise in sea level in both areas studied in the next century. Chapter VII and VIII give an assessment of physical impacts of projected sea-level rise in both lowland areas, the intertidal zone and the lowlands currently protected by sea defences in particular. Chapter IX investigates the likely impacts of the future rising sea-level on the three pilot areas. Chapter X concludes the current study.

1.2. Methodology

In order to realise the aims of the thesis, a suitable methodology should be applied. To date, however, both studies on the past sea-level changes and on the impacts of sea-level rise lack any accepted formal methodology universally applied (Tooley, 1978a, b, 1982; Shennan, 1980; Shennan et al., 1983; Barth and Titus, 1984; Shennan and Tooley, 1987; Shennan and Sproxton, 1990). The treatment of data is principally inductive and statistical rather than deductive (Andrews, 1972). The normal procedure is that information is interpreted and converted into a numerical form and then by the process of definition, measurement and classification, the data are placed into groups and categories that impose some degree of seemingly rational order upon them. The development of explanation via inductive models is the normal route, associated with the assessment of the data and comparison with other inductive results.

In practice, an inductive model has been established in the U.K. (Shennan, 1980, 1983a; Tooley, 1974, 1978a, 1982), which is described in section 2.2. The principle of the model is the interpretation of sea-level index points from stratigraphic and micropalaeontological evidence to transgressive and regressive overlaps which are then employed to establish local sea-level tendencies (Shennan, 1983a). An advantage of this model is that a sea-level index point not only represents a position of sea level but also provides information on the direction of sea-level movement. The establishment of sea-level tendencies is based on the interpretation of sea-level index points, i.e. transgressive and regressive overlaps. A regressive overlap is not necessarily related to a fall in sea level, nor a transgressive overlap to a rise in sea level. For example, in area A (Figure 1.2A.), sea-level index points from stratigraphic contacts A-B, C-D, E-F all can be interpreted as transgressive overlaps, representing an increase in marine influence. Equally, sea-level index points from contacts B-C, D-E and F-G can be considered as regressive overlaps revealing a decrease in marine influence (Shennan, 1987a). These overlaps can then be employed to establish the history of sea-level tendencies, of which, the positive tendencies are related to a rising sea-level and the negative tendencies, a falling sea-level (Tooley, 1982; Shennan, 1982). In area B (Figure 1.2B.), sea-level index points from contacts S-T, U-V and W-X can still be interpreted as transgressive overlaps, built up as positive tendencies, and related to a rising sea-level. Following the role of the model, sea-level index points from contacts T-U, V-W and X-Y have to be interpreted as regressive overlaps, from which periods of negative tendencies may be induced. However, it must be pointed out that the negative overlaps derived from stratigraphic contacts T-U, V-W and X-Y may not be related to a falling sea-level but a slowly rising sea-level, because the regressive overlaps may have been formed since coastal sediment (saltmarsh in particular) accumulation exceeds the rising sea-level. From this sort of situation it has been suggested

(Shennan, 1987b, p83) that "the estimated rates of sea-level rise associated with the termination of coastline advance were mostly 5 mm/yr (taken as a 50-year average), rising to a slightly higher maximum rate as the coastline retreated." It is very important to work out the details of stratigraphy which had responded to the changing sea-level, because a rising sea-level has been at a wide range of rates during the Flandrian Age (3-10 mm/yr, Houghton et al., 1990; or Shennan, 1987b, 2.6-45.6 mm/yr).

Secondly, this model requires that variates should come from a small homogeneous area so that the effects of between-site and inter-regional variations in geoid configuration, tidal inequalities and isostatic movements would be minimised (Tooley, 1978a). However, even within Morecambe Bay, tidal inequalities between sites are significant (see Table 7.1.), and isostatic differences between the north part and the central-south part might not be negligible (see section 5.4. for detailed discussion). Before between-site or inter-regional correlations are made, a careful assessment of sea-level index points from each site is essential. This involves quantifying the errors of the data and establishing the indicative meaning of sea-level index points (Shennan, 1982, 1983a, 1986b; van de Plassche, 1986a). On the other hand, correlation schemes based on the sea-level tendency concept offer an approach to the between-site correlation (Shennan, 1982, 1983a; Shennan et al., 1983). This method permits meaningful correlations between uplifting and subsiding areas (Shennan, 1986b; Firth and Haggart, 1989; Haggart, 1989). However, this method requires a sufficient number of variates, 40 variates for a thousand years for example (Shennan, 1982).

In order to meet the requirement of the model, the stratigraphic survey of the present study was designed to be carried out in Skelwith Pool, a very small area covering only about 2 km^2 which drains into the Leven estuary on the north side of Morecambe Bay. Stratigraphic correlation between Skelwith Pool and relatively larger areas, for instance the Leven estuary or in and around Morecambe Bay, is then emphasized in order to reconstruct a reliable sea-level history. However, the present study could not meet the second requirement of the correlation scheme, because within Morecambe Bay and as well as the Thames Estuary there are less than 40 dates for the Flandrian Age (10,000 years), which is less than the number Shennan (1982) suggested for 1000 years. In this thesis, therefore, it has been necessary to carry out the regional correlation in Morecambe Bay with great caution. Even greater caution should be paid in correlation between Morecambe Bay and the Thames Estuary, because of the obviously isostatic difference between the two areas. Furthermore, the reconstruction of sea-level history is based on a combination of the stratigraphical comparison and analysis of sea-level index points.

To elucidate the indicative meanings of the sea-level index points which stem from the interpretation of the stratigraphic survey, pollen and diatom analyses are applied. The interpretation of sub-fossil pollen data is based upon the features of the present-day pollen rain and concentration, as well as the geographical distribution of present-day pollen assemblages (Birks and Birks, 1980). Therefore the changes of pollen assemblages from samples of a borehole collected from a particular location can be inductively interpreted as the changes in vegetation through time, and then can be used to infer changes in climate and ecological environment and water level. In the same way, changes in proportions of diatom groups from samples from a borehole can be explained in terms of the lateral movement of coastline and of the intertidal zones. Diatom assemblages also give indications of changing water quality. From the combined pollen and diatom analyses, the results can then be utilised to show the relations between changes in sea level and movements in coastline.

The assessment of the impacts of projected sea-level rise will be based on the experimental evidence of coastal response to the marine hydrological conditions and the present results of study in Flandrian sea-level changes. For such particular studies, it is assumed that sea-level movements could change marine hydrological conditions in shallow waters, like Morecambe Bay and the Thames Estuary; and that coastal formations will be consequently adjusted and reach a new balance of coastal profiles, thus retreat or advance of coastlines could happen. However, these adjustments could be disturbed by human activities. For example, people have constructed sea defences to prevent sea water flooding over the coastal lowlands which have been occupied by them. If these structures are not adequate to protect the lands, properties and residents, natural hazards will still happen and be even worse.

1.3. Significance and Hypothesis of the Study

Fundamental research on sea-level changes has greatly expanded in the last 20 years, and has addressed the problem of sea-level changes at different scales and over different time periods. Since the late 1980s, strategic research on the impacts of the increasing atmospheric concentration of carbon dioxide and other radiatively active gases on the temperature of the atmosphere and the temperature of ocean water masses and hence on the volume of ocean water, the stability of glaciers and ice sheets and sea level itself has been a key subject for researchers (Barth and Titus, 1984; Bolin et al., 1986b; Robin, 1986; Tooley and Shennan, 1987; Wigley, 1989; Houghton et al., 1990).

On coastal lowlands, a rise in mean sea-level of even one metre during the next century could influence the outcome of many decisions now being made. Thousands of square kilometres of land along the coasts of the world could be lost or inundated. Beaches could retreat and protective structures may be breached. Where the land is also subsiding, the effects will be exaggerated. Damage from storm surges could also increase (Rossiter, 1962b), particularly along the lowlying coasts where economic activities are intensified. Flooding would threaten lives, agriculture, livestock, buildings and infrastructures. Finally, a rising sea-level would change the hydrological condition in shallow water, alter the dynamics of coastal sedimentation, and increase the salinity of saltmarsh, estuaries, and aquifers.

Some nations are particularly vulnerable. Eight to ten million people live within one metre of high tide in each of the unprotected river deltas of Bangladesh, Egypt and Vietnam (CZMS, 1990). Another few million people live in some insufficiently protected coastal lowlands in China (Han et al., 1990a). Half a million people live in archipelagos and coral atoll nations that lie almost entirely within three metres of sea level. Even in nations that are not, on the whole, particularly vulnerable to sea-level rise, some areas could be seriously threatened. Examples include Sydney, Shanghai, coastal Louisana, and London !

Titus et al. (1984, p2) suggested that "although action may be taken to limit the eventual global warming from rising atmospheric carbon dioxide, the warming expected in the next sixty years and the resulting rise in sea level are not likely to be prevented," because "most carbon dioxide emissions are released by burning fossil fuels" and "these fuels are abundant and relatively inexpensive to produce, a voluntary shift to alternative energy sources is very unlikely," and indicated that "even if the emissions are curtailed, global temperatures and sea level will continue to rise for a few decades as the world's oceans and ice cover come into equilibrium."

To meet the unavoidable challenge of global warming, societies will need accurate information concerning the likely impacts of sea-level rise on lowlying coastal areas in particular. It is well known that predicting the future is not an easy task, and needs a multidisciplinary approach. What is presently available in theory, methodology and technology, however, has provided possibilities to achieve the goal. To predict the likely impacts of projected sea-level rise on the coastal lowlands for example, a suitable investigation may be adopted. It is the combination of: (1) reconstructing the history of sea-level changes and coastal evolution which could provide information of what has happened during the past, for example the Flandrian; and (2) examining data recorded by modern instruments and historical records, which could suggest what has recently taken place and what is currently going on.

In this thesis, therefore, it is hypothesised that (1) the theory of Greenhouse Effect and the global warming induced sea-level rises in the next century is a likely outcome, and (2), under a similar circumstance such as a rise in sea level, what has happened in the past will more or less recur in the future, in terms of the response of coastal geography. Therefore, the aims of the thesis are focused on the reconstruction of the Flandrian history of sea-level changes and determining the relationships of the responses of coastal formation to the changes in sea level. This knowledge is applied to aid the study of impacts of projected sea-level rises in the next century on the coastal lowlands, which includes the responses of physical environment and effects of human activities. The local or regional marine hydrological and sedimentary conditions will be analyzed, and the published scenarios of sea level will be employed critically. In addition, this thesis is to meet a challenge in employing data with different time scales (thousands years, centuries and decades) to achieve the goal of the thesis. In practice, the results of the thesis would form a basis for a subsequent study in socio-economic responses.

In this study, two areas, Morecambe Bay and the Thames Estuary, have been selected for investigation in terms of Flandrian sea-level history and the likely impacts of projected sea-level rise in the next century (Figure 1.3.). Morecambe Bay is selected to study because it is an area with remaining rural feature, having less disturbance from industrial development and engineering works, and therefore with sites of great ecological importance. In contrast, the Thames Estuary is selected because the area has been a centre of civilization with extensive industrial and urban development. In geological terms, Morecambe Bay lies towards the edge of the rising glacio-isostatic centre of Scotland and in contrast, the Thames Estuary lies towards the edge of the subsiding tectonic and hydro-isostatic centre of the southern North Sea. A study based upon these contrasting backgrounds of the two areas should be able to produce a valuable result and fulfil interests of scientific and social societies.

1.4. Sites Investigated

In this section, the geological background and the nature of physical and social geography of these two areas are introduced.

1.4.1. Morecambe Bay

Morecambe Bay lies on the coast of north-west England, south of the famous Lake District National Park. The Bay, bordering the Irish Sea, extends about 25 km inland, covers some 490 km^2 in area, and receives drainage from four main catchments, such as the rivers Leven, Kent, Lune and Wyre (Figure 1.4.).

The solid geology of the catchment areas of the rivers draining to Morecambe Bay ranges from Ordovician to Triassic (Figure 1.5.) and these rocks have been described (Moseley, 1978) as follows: (a) the Ordovician rocks in the areas include the Borrowdale Volcanic Group and the Coniston Limestone Group. The former group consists of a thick pile of pyroclastic rocks varying from fine-grained tuffs to agglomerates, interbedded with numerous flows of lava ranging in composition from basalts to rhyolites, and they cover the headwaters of the catchments of the Leven and Kent. The latter is coarse conglomerates and grits interbedded with shales, forming a beach-deposit on the margin of the sea, and lies as a belt between the Borrowdale Volcanic rocks and the younger rocks. (b) The Silurian rocks consist mainly of marine sediments and show a series of bedded siltstones and mudstones with occasional sandstones and limestones. They mainly cover the middle parts of the catchments of the Leven and Kent. (c) The Carboniferous limestones, mudstones and shales are scattered along the north and east coasts of the Bay, i.e. the estuarine areas of the Leven and Kent, and on the headwaters of the catchments of the Lune and the Wyre. (d) The Permo-Triassic System is a series of sandstones and mudstones of red and grey colour, and covers the lower parts of the Lune and Wyre. Patrick (1987, p17) summarised that "in each catchment, the oldest rocks normally occur at the headwaters of each catchment and become younger seawards. The catchments also show a progression in their geology, clockwise from the lower Palaeozoic dominant in the Leven catchment, via the Kent catchment with both lower Palaeozoic and Carboniferous outcrops, to the predominantly Carboniferous rocks of the Lune catchment and the Carboniferous and Permo-Triassic geology of the Wyre catchment."

The floor of Morecambe Bay contains rocks of Carboniferous and Permo-Triassic age (Patrick, 1987). Two triangular areas of Carboniferous Limestone, continuous with outcrops on land, occupy the mouths of the Leven and Kent estuaries. These are succeeded seawards by rectangular areas of Millstone Grit on the eastern and western sides of the northern half of the Bay, continuous with outcrops on land, and separated by a medium area of Permain rocks. The Millstone Grit outcrops are known to finish at about the Heysham-Barrow line. To the south and west of this line the rocks are presumed to be entirely of Permo-Triassic in age and continuous with the outcrops in the Fylde, Furness and under the Irish Sea.

There are a large number of NNW-SSE trending faults cutting into the Carboniferous Limestones and Permo-Triassic Sandstones, which control deeply the trends of the main river valleys feeding into the Bay (Patrick, 1987). However, there is no information about the recent activity of the faults.

As a result of Flandrian marine deposition infilling into the lower parts of the estuarine valleys, landscapes of the coastal lowlands are dominated by the isolated solid hills surrounded by mosslands which have developed on the former intertidal flats and have been reclaimed for agricultural use, for instance for sheep in particular. Whilst outcrops of solid rock do occur, such as those in Humphrey Head, Silverdale-Arnside area and Heysham, the coastline of Morecambe Bay is backed by lowlying mosslands which are protected by sea defences. Serious flooding in Pilling caused by breaching and overtopping of the tortuous old defences in November 1977 led to proposals for a straighter embankment further out on the saltmarsh, combining sea defence with agricultural reclamation (NWW, 1983; Robinson, 1987).

In front of the sea defences, there are saltmarshes and saltings along the upper intertidal zones (Photo 3, for example). At the present day, the majority of the saltmarshes lie in the northern part of the Bay, and in total this area covers some 29.1 km^2 or comprises about 5 percent of the total area of saltmarsh around the British coast (Gray and Bunce, 1972). The saltmarshes of the Bay still contain small areas of species-rich brackish marsh, such as at Roudsea Wood, an extremely rare example of the transition to tidal woodland (see Photo 7 and Figure 8.9.; Kidson and Heyworth, 1979; Tooley, 1987b). Recently, the saltmarshes along the south coast and the east coast of the Bay are being eroded, such as the Silverdale saltmarsh (Photo 2). Therefore the saltmarshes around the Bay are of importance in terms of ecological environmental protection and the further reclamation in the near future.

Further seawards, there are intertidal sands which are exposed at low tides and occupy over half area of the Bay, as a result of the large tidal range, up to 10.5 m at spring tides (Pringle, 1987). The median particle diameters of the sands range between 20 and 210 microns (Anderson, 1972).

The settlements on the lowlands around the Bay have developed slowly during the past centuries, of which, Fleetwood, Morecambe-Heysham and Grange-over-Sands are the only towns with actual frontages onto the Bay and these are all 19th century developments owing their origins to the advent of the railways and their flourishing holiday resorts. Barrow-in-Furness, protected by Walney Island, is also a 19th century creation, stimulated mainly by the iron industry (Robinson, 1987). However the foundation of the present urban pattern of Lancaster had probably been laid by the Roman settlers (Freeman et al., 1966). Population had grown up rapidly during the nineteenth century, but afterwards declined. For instance, before the railway came, in 1841, Barrow was a village with some 250 people, however by 1881 the population had increased to nearly 50,000, and reached its peak population of 74,000 in 1921, but only 65,000 in 1961 (Freeman et al., 1966). Lancaster had developed to be one of the best market towns and industrial centres in north-west England in the 19th century, but afterwards its industrial adaptability has not been able to save it from the slight decline in population (Freeman et al., 1966). By the 1981 census, it was reported that, around Morecambe Bay, there were about 324,522 persons living in 82 wards which are totally or partly below 10 m contour, of which, the population in Lancaster was 45,126, and Heysham-Morecambe, 40,661. On the other hand, however, the earlier rural settlements have been either absorbed by the latter development or separated from the Bay in the past centuries by reclamation, expansion of saltmarshes and siltation of the estuaries (Robinson, 1987).

With an exception of the industries, settlements and holiday resorts mainly developed in Furness, Grange-over-Sands, Morecambe-Heysham, Lancaster and Fleetwood, the lowlands around the Bay are dominated by agricultural use. However the less artificial coastlines, lowlying mosslands and saltmarshes, Skelwith Pool and the adjacent Roudsea Wood for example, provide significant sites for assessing the impacts of the projected sea-level rise in the next century in terms of geographical changes. Robinson argued (1987, p11) that "the high value which is now attached to its importance for nature conservation, landscape and amenity will no doubt weigh significantly in any future arguments about alternative uses, and the provisions of the two County Structure Plans clearly intend that the present character of the Bay should be preserved, at least as far as predictable developments are concerned, for the foreseeable future (i.e. the 21st century)." In fact, for the 21st century, the Lancaster City Council has planned to redevelop the sea front areas at

Morecambe, and for the associated works for strengthening the sea defence system to be carried out. Clearly, these works including putting blocks of granite on the beach could in turn alter the coastal processes. It will be questioned how can the ecosystems of the Bay be preserved during the next century if sea level rises by about 1 metre.

1.4.2. The Thames Estuary

The Thames Estuary lies in south-east England. The estuary is 68 km long from the tidal limit at Teddington lock to its mouth taken on a line from Foulness Point (12 km east to Southend) to Sheerness (west edge of the Isle of Sheppey) (Rossiter, 1962a). This is called the tidal Thames (Figure 1.7., also see Figure 7.7.).

The Thames Estuary is geologically the drowned portion of the London Basin which is narrow in the west, but widens in the east to the Thames Estuary (Dobson, 1968). The river Thames and its tributaries drain the Basin into the North Sea. The Thames enters the region through the narrow, steep-sided Goring Gap, and at Reading it is joined by the Kennet, then follows a meandering course to its estuary. On the way, it receives the Colne, Wey, Mole, Brent, Lea, Roding, Darent and other small streams.

The rocks within and around the basin (Fig. 1.8.), which include chalk, sandstone (the Greensand) and clay (the London Clay), were formed during the Jurassic, Cretaceous and Eocene periods. Then, caused by the Alpine mountain-building movements in the Miocene period, they were forced to be gently folded into a broad syncline, with the strata dipping from the north and the south towards the Thames valley. After this period of folding, the newly-formed land was subjected to erosion by rain, rivers, wind, frost and other agents. The upper parts were slowly worn down and much material was carried away to the sea. In the central-south part of the basin, the London Clay was eroded to form lowlands where the Estuary is, whilst the Chalk and some sandstones were left upstanding as hills or platforms. In this way the present landscape of the Thames valley came into being (Dobson, 1968).

During the Pleistocene, part of the materials eroded from the upper part of the basin was deposited in the valley and formed the major geomorphic features apparent today, which were named the Thames river terrace sequences (West, 1968, 1972; Clayton, 1977). In the lower Thames valley, four terraces were identified: Boyn Hill, Taplow, Upper Floodplain and Lower Floodplain (West, 1972; Jones, 1981). Their formation was first explained by increased aggradation, consequent upon sea level rises during stages of the Pleistocene (King and Oakley, 1936). However, an opposite explanation suggested that discharge variability rather than sea-level change may have been the most important control on the patterns of erosion and deposition of the terrace system (Jones, 1981). According to the finds of mammalian fauna from these terraces, important conclusions have emerged (Jones, 1981). The Boyn Hill Terrace appears to be equated with the Hoxnian interglacial and the Taplow

Terrace containing a cold fauna is probably Wolstonian in age. The Upper Floodplain Terrace developed during the Ipswichian, and the Lower Floodplain Terrace probably during early Devensian times, followed by a final phase in deposition of the buried channel (Devensian) and the alluvial infilling (Holocene). Within the lower Thames Valley, the surface of Boyn Hill and Taplow Terraces are proximately at 30 and 15 m O.D. (Jones, 1981). Those of the Upper and Lower Floodplain Terraces range around 13 - 7.5 m O.D. (West, 1972). It must be noted that this famous series of terraces was extended from the Middle Thames Valley into the lower Thames Valley on the basis of their landform features (Jones, 1981), and that this sequence of terraces was accepted by other researchers (e.g. Devoy, 1979). Since litho- and biostratigraphical methods were recently applied to the detailed investigations in the Lower Thames Valley (Gibbard et al., 1988) as well as the Middle Thames Valley (Gibbard, 1985) and east Essex (Bridgland, 1988), it has been suggested that the sequence of terrace aggradations should be defined as the Gravel Formation (Gibbard, 1985).

The Flandrian sequences were developed upon a fluvially Late Devensian gravel surface between the south and north terraces of the Thames valley (Devoy, 1979). These deposits have built up the land on both sides of the Thames mainly below 5 m O.D. (Figure 1.7.). These lowlands have been reclaimed for residential, commercial, industrial and agricultural uses since the 1800s (Sinclair, 1964), and landuse changes continue to the present.

At present, the lower Thames valley is one of the areas with the most dense population and the greatest commercial value in the world. London, located on the upper Thames Estuary, is one of the biggest cities in the world and one of the most important political centres of the world. However, Fitter (1945, p27) indicated that "up to the invasion of the Roman in A.D. 43 there is no certain evidence of the existence of any permanent settlement on the famous square mile of the city, which has been the core of London for the past nineteen hundred years. ...... With the coming of the Romans the first city was built on the twin hillocks on either side of the Walbrook rivulet, and the wall was built to enclose and protect Londinium. ...... From the seventh to the eleventh centuries there was much open ground within the City walls, but thereafter London not only filled out the space within its own walls, but overspilled." Following the influence of industrialisation, the metropolitan regions of London extended rapidly. Coppock (1964, p28) described the expansion that "In 1801 the population of London was 1.1 million and its extent less than 10 km across; today the built-up area almost fills a circle 48 km in diameter and houses over 8 million inhabitants." Currently, there are over 2.3 million people living in 328 Wards which are totally or partly below the 10 m contour, based on the 1981 census.

In the new industrial age, London has many attractions for manufacturing industries (Martin, 1966). The Thames-side sites have striking advantages for industries processing bulk materials; and the premier seaport, the premier airport, and the hub of radiating roads and railways is a convenient place for the assembly and processing of the many raw materials that make up modern manufactured goods and for their distribution to markets at home and overseas (Wise, 1962). For the 21st century, new housing and industrial development is likely to be carried out in the 1990s along the banks of the Thames Estuary east to London (SURPLAN October 1990).

However, most of these advantages have been under threat from natural risks, such as Highest Astronomical Tides, storm surges and consequential flooding by the sea (International Disaster Institute, 1981), because most of the electrical generators, chemical factories, oil refineries, manufacturers and many residential areas are located on the lowlands of the Thames Estuary below the 10 m and 5 m contours and even lower, for instance, on Canvey Island. These lowlands have directly or indirectly suffered from sea flooding in the last and this century (International Disaster Institute, 1981). Before the barrier was built, the International Disaster Institute (1981) forecasted that extreme water levels at London Bridge, which represented a major flood risk, were estimated to be increasing in height above O.D. at the rate of about 2.4 ft./century (or 7.3 mm/yr) !. In order to protect the properties in the upper estuary, a removable barrier has been constructed at Woolwich Reach, and the embankments downstream have been improved and raised up to 7.2 m O.D. at Woolwich and 6.9 m O.D. at Erith. The barrier is now operable as a flood defence structure and had to be closed two or three times a year in the 1980s.

As sea level rises ever higher compared with the land levels, closures of the barrier will become more frequent. It is clear that frequent closures could cause trouble in commercial efficiency of the upstream docks and in water pollution, as well as some technical problems for the barrier operation. On the other hand, there are reasons to doubt whether the barrier and the improved embankments can reliably protect those high-valued properties during the next century when sea level rises of up to 1 metre and frequencies of damaging storm surges may be doubled. In fact, a surge level of 1 in 5 years was recorded 3.85 m O.D. at Southend at 24 December 1988, however it reached a height of 5.10 m O.D. at Woolwich when the barrier was closed (data from Thames Water, National River Authority). Therefore it is strategically important to foresee the risks resulting from the projected sea-level rise in the next century, and then to establish an 'early warning system'.

CHAPTER II

REVIEW OF LITERATURE

This Chapter reviews the history of sea-level research, and the important concepts, theories and methodologies which are already established and applied to the previous studies, as well as the principles, mechanisms and impacts of the so-called "Greenhouse Effect" and the global warming induced sea-level rise.

2.1. History of the Research on Sea-level Changes

2.1.1. Pre-1970s

Mankind has always had to face the effects of sea-level changes over many generations, and sea-level changes are recorded in many myths and early historical records. Evidence of changes from land to sea or vice versa was documented as early as the eighth and ninth centuries in China, and later in Europe. Since the eighteenth century, fundamental research on sea-level changes has been pursued along many routes, results of which from older literature have been reviewed by Mörner (1987a,b). During the eighteenth century, relative sea-level changes recorded in stratigraphic sequences were explained to be results of the change in ocean level, stability of the crust, or by the earth's rate of rotation. In the middle of the nineteenth century it became evident that sea-level is likely to have changed from the following reasons: the changes in geoid configuration, the ice ages, or ocean basin subsidence. All these theories, however, assumed a rigid earth. With the discovery of glacial isostasy in the middle and late nineteenth century, it was demonstrated that the earth was not at all rigid, but was deformed under the additional load of ice, and later readjusted to its former level when the ice melted away. In the same period, relative sea-level changes were also thought to be due to a gradual sinking of the ocean floor (i.e. tectono-eustasy) according to the formation of coral reefs.

During the twentieth century, more and more scientists directed their attention to the research of sea-level changes. For instance, the INQUA (International Union for Quaternary Research) Commission on Quaternary Shorelines was set up during the IVth INQUA Congress in Rome in 1953. It had eight objectives which were concentrated on the evolution of coastlines (Richmond, 1965). To realise the end of this programme, working groups of the commission were established in 1972, to produce a World Shorelines Map on the scale of 1:30 million, and an atlas of regional shorelines; in 1977, on hydro-isostasy and on coastal management (Grant, 1978).

The IGU (International Geographical Union), through two of its commissions and working groups from 1926 to 1984, has had an interest in similar or related aspects of sea-level, shorelines and coasts (Tooley, 1987a). The results of eight years' research have been two seminal collections: one on coastal changes (Bird, 1985), and the second on the world's coastline (Bird and Schwartz, 1985). However, since 1973 when a specific sea-level project under the auspices of the IGCP was promulgated as a joint enterprise of Unesco and the International Union of Geological Sciences (IUGS), studies on sea-level and coastal changes were further promoted.

2.1.2. Post-1970s and IGCP Projects

The IGCP, established in 1973, was designed to encourage international research on geological problems. Project 61, entitled 'Sea-level Movements During the Last Deglacial Hemicycle (about 15,000 years)', was led by Professor A.L. Bloom. The objective of IGCP 61 was to establish a graph of the trend of mean sea-level during the last deglaciation, continuing up to the present time. This graph would be an expression of the changing hydrologic balance between ice and water in response to climatic change. The individual records of relative sea-level movements from localities all over the world would be used to compile the sea-level graph. In turn, the differences among the local crustal movements along the coasts, and fundamental parameters of strength and elasticity of the earth's outer layers were to be dealt with. In the project proposal of 1974 a further objective was the prediction of future trends of sea-level, particularly in lowlying, densely populated coastal areas (Bloom, 1983).

Project 61 was carried out from 1974 to 1982 with operational phases. The first phase was the compilation and computer storage of global data, in which several thousand radiocarbon dates were obtained from coastal sites. These data were facilitated by the use of a sea-level documentation form for the collection of sample dates. This progress was hampered by both a poor return of completed computer forms and uneven quality in the content of the forms. In the UK, for instance, Dr. I. Shennan, using a simplified form, assembled 782 data points, but about half the points were rejected because they provided no evidence that they were related to sea-level (Tooley, 1987a). The second phase was the determination of key areas with deficient data. In this phase, an atlas of sea-level curves on a global scale was published (Bloom, 1977), which revealed considerable regional variations. In the UK, the retained 374 data points were displayed on maps, as frequency histograms showing the temporal pattern of dates, and as cumulative frequency histograms showing positive and negative sea-level tendencies (Tooley, 1982). Meanwhile, detailed investigation of Flandrian stratigraphy and examination of techniques employed was carried out from northwest England, which provided a valuable curve of sea-level changes (Tooley, 1978a). Similarly, a Holocene sea-level curve from the west coast of Sweden was compiled to describe the expression of regional eustasy (Mörner, 1976). The mathematical modelling and prediction was the proposal of the third operational phase. The most significant contribution in this phase includes the results demonstrated by Clark (1980). He illustrated that there was a non-uniform rise of sea-level during deglaciation resulting from a deformation of the ocean floor and a distortion of the geoid caused by a redistribution of water and ice on the earth's surface and a consequential redistribution of mass within the earth. Clark et al. (1978) subdivided the world ocean into six zones characterized by a specific form of sea-level curve: in four zones emergence was predicted, and in two zones submergence. At the International Geological Congress in Paris in 1980, it was concluded that we are no longer seeking to define a single globally valid curve of sea-level variation. The new goal is to define the history of local and regional sea-level.

IGCP 61 ended at the INQUA Congress in Moscow in 1982, and was succeeded in 1983 by Project 200. This project entitled 'Late Quaternary Sea-level Changes: Measurement, Correlation and Future Applications' and led by Dr. P.A. Pirazzoli. The aim of the project was to identify and quantify the processes of sea-level change by producing detailed local histories that can be analyzed and correlated for tectonic, climatic, tidal and oceanographic fluctuations (Pirazzoli, 1985). The ultimate purpose is to provide a basis for predicting near-future changes for application to a variety of coastal problems, with particular reference to densely populated, low-lying coastal areas (Hoover, 1983). It was emphasised that sea-level variations resulted from a complex of local, regional and global processes. The project was intended to investigate the modulating factors and their interactions, in order to attempt a definition of the temporal, areal, and altitudinal scales at which changes in sea-level occur, with associated effects on coastal and shelf deposit evolution and the separation and quantification of the causes of these changes. Thus, the fields of research involved in Project 200 were wider than those in Project 61, including data banks, physical models, tidal variations, shelf research, geoidal research, evolution of ice caps and glaciers, water-mass balance, ocean/climate changes and sea-level, astronomical influences on sea-level, neotectonics, human impact on sea-level, evolution of coastal landforms, and applied aspects of sea-level.

The operations of Project 200 comprise: (1) collection, analysis, interpretation and correlation of new and existing sea-level data, (2) survey and data analysis of coastal and shelf deposits, and (3) analysis of tide-gauge records and the modelling of other short-term sea-level fluctuation. The contributions include a number of publications (van de Plassche, 1986b; Devoy, 1987b; Tooley and Shennan, 1987; Qin and Zhao, 1987).

IGCP Project 274 was conceived from IGCP Project 200, entitled 'Coastal Evolution in Quaternary', and in part extended the work of sea-level studies. However, the project is not specifically a sea-level project. The aims of Project 274 were outlined (Anon, 1990) as: (1) Documentation and explanation of coastal evolution, and (2) understanding of specific thematic studies which are necessary to help solve problems of human occupancy of the coastal zone. These aims are to be achieved through the following scientific objectives:

1. Models of coastal evolution, including the continental shelf;
2. Coastal evolution in critical earth environment zones;
3. Impacts of sea-level changes on coastal environments;
4. Education and promotion, communication of knowledge to other audiences upon matters concerning coastal evolution and impacts of sea-level change.

It is clear that the theme of the project is mainly coastal evolution with work concentrated on the coast.

For the proposals of Project 274, the U.K. working group agreed (Anon, 1990) to make a positive effort to encourage the participation of civil engineers, coastal geomorphologists, hydrologists and ecologists. Furthermore, the objectives of the UK working group to Project 274 were agreed: to integrate existing data on shoreline evolution and sea-level history in the British Isles into a framework for exploring and predicting coastal changes; and to examine the sensitivity of shoreline response to factors such as sea-level change, sediment supply, wave power, basement geometry and basement material in such environments as gravel beaches, sand beaches, sand dunes, saltmarsh, cliff, shore platforms and engineered coasts. The results of these studies should ideally provide information for civil engineers on process-response relationships which should be considered in the design of future developments.

2.2. Sea Level and Sea-level Change

2.2.1. Definition of sea level

In broad terms, sea level can be considered as the surface of the sea or oceans. In scientific terms, it became acceptable that sea level has fluctuated through time, rather than remained static. It is well known that the attraction of the sun and moon causes tides. Independent of the effects of wind and other 'superficial' agents, the level of the surface of the sea or oceans at a given location changes continuously throughout the tidal cycle, ranging between the level of high water and that of low water, two levels which vary between spring and neap values depending on the position of the sun and moon in relation to the earth (Jardine, 1986). In the scale of the world, the spatial variation in the altitude of the tide results from the interaction of earth rotation, the shape and depth of the oceans and coastal waters and finally from coastal and offshore zone configuration.

The duration of tidal cycles varies semi-diurnally, diurnally, monthly, and even yearly (i.e. 18.61-year period). These short-term variations of sea (tidal) level have been observable since the first tide gauge was established in 1682 in Amsterdam (van de Plassche, 1986a). For comprehensive use, particular levels of the surface of the sea recorded in a location, Heysham in Morecambe Bay and Southend on the Thames Estuary (Table 2.1.), can normally be calculated. Mean Tide Level (MTL) in a location is the

Table 2.1. Typical tidal levels calculated in the U.K. (m O.D.)

Principal Tide Gauge:	Heysham	Southend
Highest Astronomical Tide (HAT)	5.60	3.50
Mean High Water of Spring Tide (MHWST)	4.50	2.80
Mean High Water of Neap Tide (MHWNT)	2.50	1.90
Mean Tide Level (MTL)	0.30	0.12
Mean Low Water of Neap Tide (MLWNT)	-2.00	-1.50
Mean Low Water of Spring Tide (MLWST)	-3.80	-2.40

average value of all the levels of high water and low water at that location, taken over a period, depending on the symmetry of the tidal curve. Mean Sea Level (MSL) occurs above or below MTL, normally with a constant value. It should be noted that, as a datum-plane for surveying, MSL is more important and is used more frequently than Mean Tidal Level (Clark, 1958). MSL as zero reference datum is, in theory, the average level of the surface of the sea as calculated from a large number of observations taken at equal intervals of time (commonly one hour) over a period of several years. For the mainland of Britain, Ordnance Datum Newlyn is the mean value of sea level determined at Newlyn (Cornwall) during the period AD 1915 to 1921 (Jardine, 1986).

However, for considering the altitude of sea-level indicators, MTL may be obtained in the field more easily than MSL (Hatfield, 1969). Thus there are advantages on certain occasions in using MTL rather than MSL as a reference datum-level (Jardine, 1986). An example of such an occasion is when the altitudes of present coastal landform are being compared with the altitudes of former coastal landform. Jardine (1982, p26) stated that, "It should be understood that Mean Sea Level, being a calculated value based on measurements made at regular intervals in the course of no longer than approximately the last 150 years, is a level of which there is no long-term record in sedimentary deposits or landforms. In contrast, Mean Tidal Level ... is a level whose (approximately) former value may be determined from the sedimentary and geomorphological record of former high tide, low tide and tidal range values. For practical purposes, eg. the construction of sea-level curves, values of former Mean Tide Level rather than of former Mean Sea Level are used (although those who construct such curves may not be aware, or may not state, that this is the case). In effect, former Mean Tide Level and former Mean Sea Level at a given site at a given time are taken to be equivalent in value."

In practice, Jardine's opinion seems to be acceptable. For the research of Flandrian sea-level changes in the British Isles, however, the MHWST is ecologically an important reference level rather than the MTL and is used more frequently (Tooley, 1974, 1978a,b, 1982; Kidson and Heyworth, 1979; Devoy, 1979, 1982; Shennan 1982, 1986b). This is because many sea-level indicators are derived from the flowering plants that grow on saltmarshes which normally accumulate around or immediately above the level of MHWST and are overlaid or underlaid by marine clastic sediments in stratigraphic records.

In the research of the impact of projected sea-level rises in the next century, all the reference tidal levels mentioned above will be considered and compared with the altitudinal data from the Ordnance Survey (or topographic data of the Geographic Information Systems) which are relative to the MSL (Ordnance Datum) in Newlyn, Southwest England. It must be noticed, however, that on the maps of the Ordnance Survey, MHW is used rather than MHWST.

2.2.2. Mechanism of relative sea-level changes

Beside the changes of the sea level in regular tidal cycles caused by the attraction of the sun and the moon, there are some other factors which contribute to the short-term changes of sea level. Probably the most common mechanism contributing to the sea-level changes in the northern Atlantic and the North Sea is the agency of the fluctuations in barometric pressure over the sea surface and the stress delivered by wind to the sea surface. In many cases, the barometric pressure is associated with wind stress. The subsequent variations in sea-level rising or falling, over or under the predicted levels of tidal cycles, are called surges (Lisitzin, 1974; Rossiter, 1962a). Other factors contributing to short-term changes of sea level include ocean temperature, salinity of the sea water, seasonal oceanic circulation, as well as tsunamis derived from earthquakes (Peltier, 1987) and from landslides on the continental slope (e.g. Long et al., 1989; Smith and Dawson, 1990). Thus, short-term changes in sea level are the sum of one or more of these components. The proportional contribution of each varies locally and regionally (Devoy, 1987a).

The existence of tidal gauge records, a few extending as far back into the past as 100 years or more, also provides useful information as to the mechanisms of relative sea-level changes which are operative on these extended timescales. On the timescale of 100 years, steric effects also seem to be an important contributor to the global scale of secular increase in relative sea-level, which appears to be characteristic of this period of earth history (Peltier, 1987). In some detail, Gornitz et al. (1982) have pointed to evidence of a warming of global surface temperature of about 0.4 °C during the twentieth century, which suggests a sterically induced rate of sea-level rise during this period of about 0.6 mm/year. This interpretation is in terms of a model of vertical thermal diffusion of the ocean. This is sufficient to explain about 50 per cent of the global rate of present-day sea-level rise, inferred on the basis of analysis of secular variations of relative sea-level recorded on a global array of tidal gauges, the records of which extend many decades into the past (Peltier, 1987)(see section 2.5. for details).

The most important source of variability of relative sea-level in a 1000-year timescale is that associated with the continuing isostatic adjustment of the surface of the solid earth in response to the melting of the huge ice sheets (Peltier, 1987). The reason why relative sea level continues to change in response to this cause so many millennia after the Canadian and

Fennoscandinavian, as well as glaciation over the Scottish Highlands had completely disappeared, is due to extremely high value of the effective viscosity of the earth's mantle. This viscosity governs the rate at which mantle material flows in the process of restoring the deformed shape of the earth to one of gravitational equilibrium (Clark et al., 1978). This process is called '*Glacial Isostatic Adjustment*', and will be discussed in detail in section 2.4.

On a timescale of 10 ka to 1 Ma, the dominant contributor to the relative sea-level changes has been the continuous process of accumulation and disintegration of large ice sheets, such as that which last covered Canada and Fennoscandinavia 18,000 years ago. When the ice sheets which covered these areas and Greenland and Antarctic were at their maximum extent, they caused a global eustatic fall of sea level (glacio-eustasy) over 110 m (Peltier, 1987). The lowest stand of sea level during the last glacial maximum, 121$\pm$5 metres below present level, was recorded according to Fairbanks' (1989) analysis of coral reefs drilled offshore of Barbados. The extremely large amplitude glacio-eustatic variation of global sea level which accompanies the 'Ice Age Cycle' (Goudie, 1983) suggests the operation of a further important mechanism of relative sea-level change. In Peltier's (1987) description, there will be an important contribution to the *observed* variation of relative sea-level resulting from the direct effect of the water load applied to the ocean basins as the ice sheets melt. This is to be gleaned from analysis of relative sea-level data during times of active ice sheet disintegration at sites near the glaciated regions, or at any time from sites well removed from the ice sheets. This water load will in turn induce its own deformation of the solid earth. This process is called *Hydro-isostasy* (Bloom, 1967).

2.2.3. Sea-level change definitions

Records of past sea-level change are based either on regular measurements by means of tide gauges, or on interpreted field evidence which may have a vertical relationship to one or other local water levels (van de Plassche, 1986a). The water-level relationship of physical, biological and other features originating in coastal areas is called the indicative meaning of a sea-level indicator (Shennan, 1980), which will be discussed in detail in later sections.

Van de Plassche (1986a, p9-10) has indicated that "A fundamental requirement of quantitative comparison of sea-level change records from different sites or areas is, that the sea-level considered does not change its spatial configuration relative to the geoid with time. .... In terms of factor hierarchy, one can say that the geoid carries mean sea level which in turn carries the tidal wave, from which characteristics of mean tidal level is derived, and which is one of the factors controlling ground water level related to tidal level." The geoid , as a global reference surface for heights, is the equipotential surface of the earth's gravity field that best fits mean sea level in the least spatial square sense (Mather, 1975). The geoid, with its maximum relief difference of about 180 m (-105 and +75 m), is a function of the earth's rotation and mass anomalies.

Therefore, sea-level change can be defined as the departure of mean sea level from the geoid. Provided a stable geoid in short-term (less than 100 years or even 1000 years), sea-level change can be considered to be a net change in height of the wave-smoothed surface of the sea between two moments in time as measured at a given locality. For the longer term such as the Flandrian (Holocene), however, this definition may be applicable for the derived sea-level change, provided the sea-level indicators relate, or can be converted, to the same reference water level and have been obtained from the same locality (van de Plassche, 1986a). If two samples come from different sites, they must fulfil the requirement that the height of each derived (converted) sea level is representative for the other sampling site. In case a change in sea level is evident and cannot be quantified, or there are no derived sea-level heights to be compared, the change in sea level observed is expressed as the (positive or negative) direction(s) of change of a given reference water level prior to or since a point, or between two points, in time at or within a given locality or area (van de Plassche, 1986a).

Van de Plassche (1986a) indicated that recorded sea-level change resulting entirely from land-level movements is referred to as apparent, whereas it is called real in case no land-level changes are involved at the recording site. The result of simultaneously occurring real and apparent sea-level changes is termed relative sea-level change, which term also applies to any sea-level change record or graph for which the contribution of apparent sea-level change is unknown.

In short, changes in global mean sea-level (eustatic changes) are essentially synchronous on a worldwide scale, whilst relative sea-level changes vary in nature and amount from place to place. The field evidence surviving in any one area tends to record the changes of relative sea-level resulting from the interaction of movements of the sea surface with changes in the configuration of the land. It is often by no means clear to the investigator whether the submergence or emergence affecting his particular site is likely to form part of a sequence similar to or quite different from events elsewhere (Morrison, 1976). Therefore, some workers have sought to identify areas of crustal stabilities, which would serve as direct measuring marks against which eustatic changes might be traced (Fairbridge, 1961). Against this approach, Newman and Munsart (1968), for instance, have gone so far as to state that coastal stability is a myth, and doubt that any coast has remained stable during the Pleistocene epoch. Recent geophysical work on hydro-isostasy would endorse such doubts by indicating that the continental margins respond to loads of the order involved in Holocene sea level change (Walcott, 1972; Newman et al., 1980). At the present state of knowledge, it would seem advisable not to rely on the concept of 'stable areas', but to consider it probable that all available data may involve movements of both land and sea surfaces.

2.3. Interpretation of Palaeo-sea-level

2.3.1 Sea-level indicators

Every marine feature or organism which has a quantifiable vertical relationship to a water level, the height of which is ultimately controlled by tidal amplitude at the coast (Jelgersma, 1961; van de Plassche, 1982), can be regarded as a sea-level indicator (Devoy, 1987a). Sea-level indicators may normally be identified or interpreted from field evidence and thus associated with stratigraphic, altitudinal and age information, so that they have been used as sea-level index points to construct sea-level curves. For instance, in the British Isles, the most common and reliable indicators are salt marshes which can be found in the Flandrian stratigraphy, underlying or overlying marine clastic sediments, and can be radiocarbon dated. On the other hand, presently, salt marshes normally grow upon silt and mud flats in the sheltered coasts and within the limits between MHW and the upper limit of marine activity.

For highlighting the imprecise nature of much of the evidence, van de Plassche (1977) produced a draft of a manual, largely concerned with the evaluation of the 'water level indicators'. Kidson (1982) also indicated that the only wholly reliable indicators are organic remains in growth position where relationships to sea level or to water table can be determined within acceptable limits.

In northwest England, Tooley (1974, 1978a,b, 1985a) has used three criteria to investigate and select sea-level indicators. He indicated that reconstructing sea-level history in detail should be based upon the sea-level indicators which (1) should come from a small, homogenous area, so that the effects of tidal inequalities, earth movements and variations in geoid configuration would be minimised; (2) should be based on material from similar palaeoenvironments and have the same indicative meaning (see Section 2.3.2.); (3) should be radiocarbon dated and should be capable of independent corroboration, which can be achieved only where standard regional pollen diagrams are available and a chronozone system established.

The application of these criteria (Tooley, 1978a,b) has led to an overhaul of the nomenclature used in sea-level studies (Tooley, 1982; Shennan, 1982) and the establishment of a sound basis for correlation (Shennan et al., 1983). Shennan (1980) further defined the term 'tendencies of sea-level movement' which can be positive or negative. A sea-level indicator is site-dependent, but indicators from a wider area show a general tendency of sea-level movement, which is the basis for wider correlations. Shennan et al. (1983) have demonstrated that correlation schemes based on the sea-level tendency concept offer an alternative to the comparison of sea-level curves and marine transgression sequences, which also permit correlation between rising and subsiding areas.

2.3.2. Indicative meanings of the indicators

Godwin (1940; also see Tooley, 1986) speculated on the relationship of peat to its contemporary water level: a relationship now referred to as the 'indicative meaning'. He showed that freshwater peat did not form below (mean) sea level, and that at the seaward end of a tidal river, freshwater peat cannot form below the high water mark of ordinary spring tides, for which a figure of +10 ft O.D. was given for East Anglia. High saltmarsh peat containing Phragmites or Juncus maritimus was indicative of an early high water mark: as the tidal wave extinguished upstream, so the altitude of saltmarsh peat would decline in altitude towards mean sea level. The indicative meaning of these peats would depend on an estimation of the position of the palaeocoast.

Recently, Shennan (1986b, p156) indicated that "the indicative meaning of a dated sample is the relationship of the environment in which it accumulated to a reference tide level." Van de Plassche (1986a, p17) also indicated that "the water-level relationship of an (sea-level) indicator can be a major source of error. ...... Ideally, a water-level relationship should be based on long-term and widespread measurements and observations to account for temporal variability of the reference water level and to know and understand the height variability of the indicator as a function of environmental and other factors." He further argued that in practice this ideal may not be feasible, therefore references and the observational data base should always be mentioned and taken into account when determining or evaluating the indicative range of a fossil sea-level indicator.

Shennan (1986b) pointed out that, in macrotidal areas, an assessment of the correct indicative meaning for a sample will be more important than in microtidal areas, and that the most important is the transition between fenwood and reedswamp. This is because that fenwood peat will start to form at MHWST in a coastal fen, but in a backswamp area the local groundwater level may be the controlling factor and this may be around MTL (Godwin, 1940). Based on the studies of Flandrian stratigraphy in the Fenland, he has estimated the values of indicative meaning for contacts between peat and clay deposits (Table 1, Shennan, 1986b), and stressed four main points: (a) the indicative meaning is dependent on the type of stratigraphic overlap under consideration, (b) the reference water level for each type of indicator should be given as a mathematical expression of tidal parameters rather than a single tide level $\pm$ a constant factor, since the constant factor will indicate quite different tidal inundation characteristics for areas of different tidal range, (c) the indicative range can be reduced by dating the level at which the pollen, diatom, macrofossil and stratigraphic evidence reveal a change in the sedimentary environment, therefore dated samples from the middle of homogenous peat layers are less useful, and (d) the accuracy of reference tide-levels must be assessed.

It has been pointed out (Kidson and Heyworth, 1979) that the upper limit of salt marsh is the point somewhere between MHWST and the upper limit of marine activity, i.e. storm conditions during high water of Equinoctial Spring Tides. In Morecambe Bay, salt marshes are confined to the upper 2.5 m of the very large tidal range which (9.5 m from MHWST to MLWST) results in a highly unstable intertidal system, and at least four types of saltmarsh vegetation have been recognised with relationship to the tidal levels (Gray and Scott, 1987). Based on this research, the range in altitude of indicative meaning of the sea-level indicators derived from salt marsh deposits in Morecambe Bay can therefore be determined. However, this determination is only site- or small region- independent, because tidal range varies between different sectors of the coast (see Table 7.1. and Figure 7.1.).

2.3.3. Tidal variation

Large variations in tidal range can occur over quite small distances. Kidson and Heyworth (1979, p7) stated that "even in macro-tidal environments, where tidal range cannot be ignored, errors have been introduced by failure to appreciate the wide variations in tidal level caused by local coastal morphology. In many bays and inlets, which are narrow and shallow, tidal height and range increase dramatically landwards." These phenomena definitely occur in Morecambe Bay and the Thames Estuary (see Chapter VII). Kidson and Heyworth (1979, p7) also indicated that "the relatively wide spacing of tidal recording stations makes the accurate calculation of tidal levels from tide tables extremely difficult for intermediate locations. At several places on the British coast the height deduced from tide tables is significantly lower than that recorded on site." For instance, "In the estuary of the Leven in Morecambe Bay the computed height of MHWS is 0.9 metres lower than the actual height. This arises entirely from distance from the nearest reliable tide gauge."

Before sea-level indicators (or index points) from regions with differing tidal ranges can be compared, adjustments for tidal variation must be made. It has been stated (Kidson and Heyworth, 1979, p7) that, "the curves (of sea level) from the Bristol Channel and Cardigan Bay in Britain, when plotted in relation to local high water levels appear to differ. When the tidal adjustment is made, they are the same curve," and that, "when similar adjustments are made to the curves from the Thames Estuary in southeast England and Morecambe Bay in northwest England, the real differences between them become apparent."

However, for comparing the sea-level indicators which come from a relatively large region, like Morecambe Bay and the Thames Estuary, similar adjustments are still necessary. Kidson (1982, p133) indicated that "frictional forces in such shallowing and narrowing arms of the sea result in the enhanced tidal ranges to be found there. ...... this means that the height of high water above the geodetic datum is also increased." In fact, the height of MHWST above O.D. increases 1.1 m from the mouth (Southend) to the head (London

Bridge) in the Thames Estuary, and 0.4 m, Morecambe Bay (see Tables 7.1. and 7.7.).

A basic assumption made by many sea-level investigators in constructing sea-level curves was that the tidal range had remained constant as sea-level changed (Tooley, 1985). However, Grant (1970) argued that tidal amplification was non-linear and probably exponential with time, and that the increase in tidal range in the Bay of Fundy (Canada) began about 6000 BP but most of the increase occurred during the last 4000-5000 radiocarbon years. He concluded that the increase was controlled by water depth, not by the width of a dilating bay. Using a numerical tidal model and some new empirical data, Scott and Greenberg (1983) have shown that tidal amplitude in the Bay of Fundy increased more rapidly during the period 7000-4000 BP than in the period 4000-0 BP. They calculated an average increase in tidal amplitude of 1-2 percent with each 1 m rise in sea level. Roep et al. (1975) and Roep and Beets (1988), by their empirical research in the Netherlands, supported these results that the more rapid rise in sea level the greater increase in tidal amplitude would occur.

In Britain, Davis (see Tooley, 1985a) also suggested that significant changes have occurred in the amplitude of the semidiurnal tide when the altitude of the sea-level surface was reduced by 20 m (9500 BP), 10 m (8500 BP) and 5 m (7500 BP). In Liverpool Bay, the amplitude of the M2 tide was reduced from c. 2.8 m to c. 1.8 m when sea level was lowered by 20 m. At the head of the Bristol Channel the reduction was from c. 4.3 m to c. 1.5 m, but at the mouth of the channel there was a slight increase in amplitude from c. 2.2 m to c. 2.3 m over the same period.

A slight rise (or fall) in sea level would, therefore, cause a increase (or reduction) in the amplitude of the M2 tide in a shallow (and narrow) area, like a bay or estuary, rather than in a deep water area, like the Irish Sea and the mouth of the Bristol Channel (Devoy, 1987a). This is probably because that, in a funnel-shaped embayment (estuary), tidal amplitude often rises landward, due to the confinement of the tidal wave as it progresses up-estuary, which is called the 'estuary effect' (Fairbridge, 1961).

Tooley (1985a) stated that this factor is important in any evaluation of the altitude of sea-level index points, as the tidal amplitude may have increased by as much as 5.5 m in 4500 radiocarbon years in some areas (Scott and Greenberg, 1983), thereby affecting the succession of coastal plant communities which are the raw material for palaeocoastal reconstructions. Studies of the amplification of the tidal range rank in importance with those of sediment consolidation.

2.3.4. Sediment consolidation and compaction

In theory, all sediments undergo consolidation, the rate of which is a function of time, drainage and load, either under their own weight or from overlying sediments (Tooley, 1978a). Jelgersma (1961) has reviewed some of the literature on the consolidation of sediments, and stressed that consolidation of deposits with a high sand fraction is very low, whilst consolidation of peat may be as high as 90 percent by volume. As there is a great variety of unconsolidated sediments in Flandrian coastal deposits, consolidation can vary from 0 to 90 percent (Jelgersma, 1961).

The term consolidation, as used by civil engineers, is synonymous with the physical process of gravitational compaction. However, in the geologist's sense, consolidation refers to a variety of processes including not only compaction but also cementation and recrystallisation (Greensmith and Tucker, 1986). But, the last two processes of sediment consolidation will not be considered and the sediment compaction is regarded in a vertical sense during the following discussions.

Based on the Holocene stratigraphic investigation in the coastal plain near Avonmouth, Skempton et al. (1969) indicated that all samples must be at a lower elevation than when they were originally deposited, owing to compaction of underlying strata by the weight of material subsequently laid down above the sample. In order to estimate the amount of compaction which has occurred it is necessary to know the effective vertical pressures acting in the underlying strata (i) when the sample was deposited and (ii) at the present day; as well as the change in thickness of a particular clay or peat caused by an increase in overburden load.

From the known densities of the various clays and peat layers, and from piezometric observations, Skempton (1970) has evaluated the present day effective pressures at two sites, and argued that similar calculations of a more approximate nature can be made for the other sites by using analogous piezometric conditions and reasonable assumptions of density. He calculated the effective pressures of any particular stratum at the time of deposition. These figures were based on the same assumptions of density, with a further assumption that the ground water conditions were then hydrostatic from a level just below the marsh surface. In order to estimate the change in thickness of a stratum corresponding to an increase in the effective pressures, they constructed the relationship (sedimentation compaction curves) between void ratio and the effective pressures. These calculations took into account the fact that clays deposited on tidal flats have a water content equal approximately to their liquid limit. From such curves, the compaction of any stratum can be calculated.

Luo (1981), in the Pearl Delta, Southern China, based on the detailed measurements of pore ratio and water content for the Holocene sediments and the present-day deposits, has calculated the compaction in volume of sediment bodies. He indicated that the compaction of the estuarine silty clay which was deposited during the last 2500 years varies from 11.16 percent to 11.9 percent with an average value of 11.53 percent in volume; and that of silty clay deposition during the period of 5000-7500 years B.P. varies from 33.23 percent to 43.0 percent with an average value of 38.11 percent in volume.

Luo's work suggested that, apart from a result of stresses due to overburden load, sediment compaction seems to strongly relate to sediment particle size, the associated void ratio and the length of time.

However, until more field data are collected and laboratory experiments carried out for a wide range of lithological successions, all assessments should be regarded as tentative and approximate. Greensmith and Tucker (1986) stressed that the reduction of voids within a sediment prism is dependent on a range of factors including lithology, mineral content, particle size and shape, water content, pore-water pressure, liquid limits, drainage, rate of loading, maximum effective stresses and initial thickness. The reduction would occur more readily in organic sediments and argillaceous sediments than in sands and sandy gravels. Indeed, the behaviour of peat under stress is quite different from any other unconsolidated sediments. Mac-Farlane (1965) has described that the settlement characteristics of peat as a function of time:

(a) Primary consolidation occurs extremely rapidly when a load is applied, and this consolidation can account for up to 50 percent of the total settlement.

(b) Secondary consolidation occurs slowly, and takes the form of a type of viscous or plastic movement especially if the water content changes or decay accelerates. The length of time taken for secondary consolidation is not known, but Barden (1968) notes that 'certain peats appear to give a secondary settlement linear with log-time, that appears to extend indefinitely, although it must cease eventually'.

Apart from the compaction due to a overburden load, dewatering due to artificial drainage could also cause compaction of organic sediments. A range of values of ground altitude reductions in Deanholme Moss adjacent to Skelwith Pool in the past 11 years following drainage was reported from 145 mm/year to 54 mm/year (Nijhof and Tooley, 1990).

Summarising the work mentioned above, it likely seems that: (a) within a relatively short time after a load is applied, the peat could be compacted very quickly as dewatering and compaction with a value of consolidation as high as 30 percent in average, and this situation could be applied to consider the peat deposits which are overlaid by a thin layer of minerogenic deposits, like the peat bed in the profile at Arnside Moss described by Tooley (1987b); and (b) in the long term after a heavy load is applied, the consolidation of peat deposits could account for up to 50 percent of the total thickness of the peat layer, like the basal peat under Morecambe Bay (Tooley, 1987b).

2.3.5. Coastal responses to sea-level change

In recent years there has been a growing awareness of increasing shoreline erosion on a world scale (Bird, 1976). However, Bird (1985) argued that sea-level rise is only one of the fourteen factors explaining such widespread erosion.

There are a number of factors which control the macro-scale development of coastal morphology: (1) the rate of sea-level variation, (2) the morphology and angle of the slope over which the sea level rises and falls, (3) the textural nature and volume of sediment available in the littoral zone, (4) the wave climate which directly records the degree of storminess experienced at the shoreline and, (5) the interaction between these factors leading to the preservation of the morpho-sedimentary facies upon which the coastal morphology is based (Orford, 1987).

At the core of any analysis of sea-level variation must be some assessment of the rate of sea-level rise or fall. The rate of sea-level change is very important as an independent control on the reaction of any coastal environment to process. Orford (1987) has stated that as most of our contemporary coastal morpho-sedimentary environments have been directly affected by events of the last 20 ka, they must reflect the change in coastal response associated with the rates of sea-level change between 100 and 1 mm/yr. In particular, Tooley (1978a) considered the rate of biogenic sedimentation (Phragmites peat) in the tidal flat and lagoonal zone in Downholland Moss, north-west England, and indicated an estimated rate of rise in sea level to be 34 mm/yr during the eighth millennium. Furthermore, Shennan (1987b, p83) indicated that" the estimated rates of sea-level rise associated with the termination of coastline advance were mostly 5 mm/yr (taken as a 50-year average), rising to a slightly higher maximum rate as the coastline retreated."

Coastal slopes affect coastal morphology on the basis of three factors (Orford, 1987): shoreline wave energy budget, tidal range at the shoreline and rate of shoreline migration. On an open coast, the rate of change in water depths in a shorewards direction, particularly in the nearshore where depth is less than half the incident waves' wavelength, controls the rate at which wave deformation takes place as waves move into shallow water. However, tidal range places an important role on coastal process in a shallow embayment such as Morecambe Bay, where the tidal range is in excess of 6 m, and water depths vary from 0 to over 50 m (the Lune Deep) below O.D.

Orford (1987) indicated that coastal deposition morphology is determined by the availability of sediment as well as by the textural composition of such material. By geological standards the volume of sediment currently available in the littoral zone, per unit time, is considerably greater than that available within most former depositional cycles of the geological column. This increased beach volume is a partial function of a rapidly rising but variable postglacial sea-level sweeping up the continental shelf debris.

On low-angle shelves (such as the northeastern part of the Irish Sea), the volume swept up for a given sea-level increment will be more than that obtained on a steeper shelf. However, Orford (1987) demonstrated that the coastal sediment volume is not related solely to shelf slope, as the sediment texture will determine the proportion of volume residing in the littoral zone. Silts and clay will disperse over the shelf, leaving sand and gravel in position, whilst any contemporary terrestrial sediment input may also influence coastal depositional patterns. Rapid phases of marine inundation can promote the development of littoral sedimentation at all points along the shoreline, albeit at variable sedimentation rates due to variable longshore wave energy.

2.4. Terminology in Sea-level Research

Precise definition of the terms employed in sea-level research is necessary. For instance, it was argued (Shennan, 1980, 1982; Tooley, 1982) that: the terms transgression and regression have led to numerous problems in sea-level research due to the lack of precise definitions. As a result, it has not been possible easily to correlate between the results of different research workers and subsequently the identification of regionally significant changes in sea level, associated processes and the accurate estimation of rates of crustal movements are not possible. Up to date, a series of terms has been applied and recommended in recently published articles by many authors. Definitions of some of these terms which will be employed in the present study, is summarized in the follows.

2.4.1. Transgressive and regressive overlaps

Transgression and regression were commonly used in published literature as chrono-stratigraphic units, or litho-stratigraphic units, and as processes. Shennan (1980, 1982) has suggested that these terms must not be used in any formal sense or correlation scheme, if the inconsistencies of the past are to be avoided. They remain most widely used as indicating processes, but even then their precise meaning should be defined. Perhaps it would be better to use alternative phrases to avoid further problems of comparison (Shennan, 1983b). Therefore, the marine sedimentation in the Flandrian should be considered as a geological phase. Flandrian Transgression can be divided into numbers of sub-phases based on detailed stratigraphic analysis, i.e. the interpretation of advance and retreat of marine sedimentation.

Transgressive and regressive overlaps are currently used as litho-stratigraphically descriptive terms in which no process is implied (Shennan, 1982; Tooley, 1982). Shennan (1983b, p17) stated that "transgressive and regressive overlaps are terms describing a change in sediment type, the interpretation of this change is the next stage of analysis and neither this interpretation nor the designation of a chronological unit, 'a period of marine incursion', is the correct usage." Thus, it can be summarized that transgression and regression should be emphasized to be phases or processes of marine or terrestrial sedimentation; but transgressive and regressive overlaps should be emphasized as changes in sediment type, providing evidence of marine sedimentation on land or the opposite.

2.4.2. Sea-level index points

Sea-level index points are the data points which are plotted on a time/altitude graph to illustrate vertical movement of sea level. The concept of the points was developed in the IGCP 61 guidelines (van de Plassche and Preuss, 1978; van de Plassche, 1982) to be a reference to sea levels through time. In practice, transgressive overlap and regressive overlap are just two types of sea-level index points. When sea-level index points are plotted on a time/altitude graph, employing the convention, each index point should be shown as a transgressive or regressive overlap with an error box which demonstrates the range of the indicative meaning and the two standard deviations of the radiocarbon date (Tooley, 1982). However, it must be noted that an individual sea-level index point is unlikely to show unequivocally a regionally significant process such as a rise or fall in sea level (Shennan, 1983b).

2.4.3. Tendency of sea-level movement

It must be noted that transgressive and regressive overlaps do not equate with a rise or fall in sea level. For instance, a rising sea-level might not always cause shoreline retreat in the sites where the rate of coastal deposition is higher than that of the rate of the rising sea-level. On the other hand, a regressive overlap need not always indicate a fall in sea level since the altitude variation of the overlap may show that it was formed at that specific location while the regional direction of change was an increase in the marine influence. In view of the uncertainties that may exist in any one locality, it would seem desirable to approach the problem of assessing the role of the eustatic component by comparing the patterns of change recorded at a large number of sites (Morrison, 1976). Shennan (1983, p18) further suggested that "by comparing all available lines of evidence, i.e. radiocarbon dated sea-level index points, undated sea-level index points, lithological changes, archaeological and palaeo-botanical evidence, the processes operating on a wider scale may be interpreted in terms of the dominant tendency of sea-level movement." On a regional scale, Tooley (1985a) also indicated that not only can this type of sea-level index point be used but also additional data from the perimarine and dune landscapes from a natural or archaeological context can be used to reinforce the index points showing the tendency of sea-level movement. Therefore, following the analysis of stratigraphic sections and the assessment of errors relating to the age, altitude and meaning of numerous sea-level index points, the accumulated evidence of the local sea-level index points can be interpreted in terms of the dominant local sea-level tendency.

2.4.4. Eustatic and relative sea-level changes

Eustasy was first defined as the changes in water volume of the oceans as opposed to crustal movements, and as it was always thought to affect the oceans globally, eustasy was also defined as worldwide simultaneous changes in sea level as distinguished from local sea-level changes (Mörner, 1980a). In some cases, the eustatic sea-level changes are considered as the changes of the ocean level itself, i.e. absolute sea-level changes (Mörner, 1987b). It was argued that the eustatic curve could only be recorded in so-called 'stable areas' (Shepard, 1963). However, it has been accepted in the last decade that the crust has been changing in altitude and thickness through time (Clark et al., 1978). Therefore, Mörner (1980b, p282) suggested that "the eustatic curve could only be established in all its details in a suitable uplift area where the field studies could be undertaken in full detail and the eustatic (oscillating) and isostatic (smooth) factors could be separated." He (1980b) further suggested that "the old concept of eustasy and its global validity must be accordingly changed, and the best definition of eustasy is simply ocean-level changes regardless of causation and implying vertical --- global and local --- movements of the ocean surface at a particular point." Recently it has been suggested that eustatic changes may be brought about by glacio-eustasy, tectono-eustasy, geoidal eustasy and dynamic sea-surface changes (Mörner, 1987b). In contrast, the relative sea-level changes are the combined effects of all factors that may have affected the level of the oceans and the coastal level, and can be directly determined in the field (Mörner, 1987b).

Since eustatic variations characteristically occur simultaneously everywhere, if a high degree of synchronism in coastal changes was present overall, across a diverse range of local conditions, this would suggest strong eustatic control. On the other hand, if this was not so and local factors predominated in determining the details of changes in marine influence, any geographical patterns in the timing of changes might help to identify the noneustatic factors which would be most important in different types of area.

2.4.5. Isostasy

Isostasy in geology and geophysics refers to the condition of equilibrium established by the earth's lithosphere, which essentially 'floats' on the asthenosphere (Fairbridge, 1983). Isostasy and eustasy are two intimately related geodynamic processes that can scarcely be understood or measured apart from each other. In the Quaternary, dis-equilibrium and equilibrium of the earth's lithosphere had actually occurred, being caused by the transference of loadings. During glaciations, for instance, water loading on land in the form of ice was increased. This ice then melted and flowed from land into the oceans during deglaciation. In other words, when an area is glaciated, depression of the land occurs under the weight of the ice-load; but after deglaciation the area will begin to undergo rebound to the position before glaciation. In areas peripheral to the glaciated regions, however, it is suggested (Walcott, 1972; Newman et al., 1980) that these areas could have bulged during glaciation, but collapsed during the deglacials. These processes of the re-equilibrium and equilibrium of the earth's lithosphere are named 'glacio-isostasy' (Mörner, 1987b). This has taken place in the British Isles. In Scotland and part of northern England uplift has occurred, and indeed is still occurring on Scotland, whereas in the southeast England subsidence following deglaciation in the last 9,000 years (Flemming, 1982; Shennan, 1989) has been recorded and is being recorded.

Beside the glacio-isostasy, a local event of isostasy caused by sediment loading was recorded in Mississippi delta (Fairbridge, 1983). It therefore seems that postglacial subsidence in certain areas, such as deltas or bays, is not only caused by water loading but also by sediment loading. For estimating the amplitudes of this type of isostatic subsidence, it is assumed (Newman et al., 1980) that the weight of a column of water of a unit cross section area plus the weight of the column of late Quaternary sediment equals to the weight of mantle displaced. In order to express this relationship, a formula was given:

$$Tw \times 1.03\ g/cm^3 + Ts \times 1.9\ g/cm^3$$
$$= (Hl - He) \times 3.4\ g/cm^3$$

in which, Tw is the height of relative sea-level rise; Ts is the thickness of late Quaternary sediments; Hl is the elevation after isostatic adjustment; He is the original elevation, and the 1.03, 1.9 and 3.4 g/cm^3 are the densities of sea water, late Quaternary sediments and the upper mantle, respectively (Newman et al., 1980). In a similar way, Andrews (1973) discussed that, providing an estimated ice thickness of 2000 m, the length of the crustal flexural parameter of 50-200 km and densities of 0.9 and 3.37 g/cm^3 for ice and mantle materials, depression in Northern Irish Sea may have been 400-500 m.

2.5. Greenhouse Effects

2.5.1. Greenhouse gas concentrations and global warming

Humans' expanding activities have reached a level at which their effects are global in nature. The natural systems, i.e. the atmosphere, land and sea as well as life on this planet, are clearly being disturbed (Bolin et al., 1986b). It is indicated (Callender, 1938; Budyko, 1982; Clark et al., 1982; CDAC, 1983; Wigley, 1983, 1989; Barth and Titus, 1984; Jones et al., 1986; Houghton et al., 1990) that some natural trace gases in the atmosphere, such as carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), tropospheric ozone (O_3), H_2O vapour and aerosols, have been increasing during the last century. In addition, other gases are being emitted that are not naturally part of the global ecosystem, notably chlorofluoro-carbons. These trace gases have been referred to collectively as 'greenhouse gases' due to their influence on the earth's climate.

The reason for concern about climatic effects is the so-called 'greenhouse effect' enhanced by radiatively active, naturally-occurring and synthetic gases. For example, Bolin et al. (1986a, p2) indicated "while CO_2 is transparent to incoming short wave radiation from the Sun, it absorbs outgoing long wave radiation and re-emits this energy in all directions. Therefore, an increase of the atmospheric CO_2 concentration leads to a warming of the earth's surface and lower atmosphere. In addition, it is becoming increasingly clear that a number of other greenhouse gases in the atmosphere similarly affect the radiation budget. Their concentrations are also changing as a result of natural and human causes." Since increased concentrations of CO_2 as well as of these other greenhouse gases all lead to a warming of the earth's surface and lower atmosphere, the estimated climatic effects and further impacts (e.g. on sea level and agriculture) must be considered as a result of a combined effect of these potential origins of warming. However, the relationship between the atmospheric thermal regime and the level of CO_2 concentration is of importance in understanding climatic changes.

The realization that the climate might change as a result of emissions of carbon dioxide into the atmosphere is not new. About one hundred years ago, Arrhenius (1896) pointed out that the burning of fossil fuels might cause an increase of atmospheric CO_2, thereby changing the radiation balance of the earth. During the 1930s Callendar (1938) for the first time indicated that an increase in atmospheric CO_2 concentration due to modern man's economic activities would result in global warming. Afterwards, more careful assessment of the likely CO_2 increases due to fossil fuel combustion was made by Revelle and Suess (1957), and by Bolin and Eriksson (1959).

Since the late 1950s the concentration of carbon dioxide in the atmosphere has been observed with the help of precise instruments. Observation results obtained at Mauna Loa and the South Pole during 1959-1968 showed the concentration of carbon dioxide in an increasing rate of 0.74

ppm/yr (or 0.25 percent). By 1974 the increase reached 1 ppm/yr (or 0.34 percent) (Olson et al., 1978). In recent years, direct measurements have shown that the CO_2 levels have risen from 315 ppm in 1958 to 343 ppm in 1984 (Bolin et al., 1986b) and to over 350 ppm in 1989 (Wigley, 1989) and 353 ppm in 1990 (Houghton et al., 1990). It is also concluded (Budyko, 1982) that over the last 110 years the amount of carbon in the atmosphere has increased by 72×10^{15} to 83×10^{15} g. Over the same time, the amount of CO_2 released by burning fossil fuels and manufacturing cement contained 127×10^{15} g of carbon. The amount resulting from cutting forests and cultivating the soil was about 70×10^{15} g. It is believed that 40 percent of anthropogenic CO_2 has remained in the air, 20 percent has gone into the oceans, and 40 percent has gone to the biosphere.

In pre-industrial (1750-1800) times, the levels of CO_2 were reported at about 260-270 ppm (Wigley, 1983) or 280 ppm (Wigley, 1989), based on indirect data and direct measurements from ice cores. The pre-industrial levels of CO_2 were also recorded at around 290 ppm (Stanhill, 1982). The values (A.D. 235 to A.D. 1850) derived from tree-ring C^{13} and C^{14} varying between 240 and 310 ppm and average 276 ppm were indicated (Stuiver, 1986). At a recent World Meteorological Organization meeting, the conclusions were made (Fraser et al., 1986) that a pre-industrial background of CO_2 concentration for the northern hemisphere of 286($\pm$7) ppm was found, based on six independent observations, or 280($\pm$12) ppm, based on 13 different sampling locations.

Compared with their pre-industrial levels, CO_2 concentration in the atmosphere were lower (about 200 ppm) during the last glacial period (60,000 to 15,000 years ago), a time when the global was 4-5 °C cooler than today (Wigley, 1989). On a 1000-year time scale, it is obvious that the global has warmed considerably since the last glacial period, which more or less coincides with the increasing concentration of greenhouse gases in the atmosphere. Nevertheless, measurements from ice cores going back 160,000 years showed (Figure 2.1.) that the earth's temperature closely paralleled the amount of carbon dioxide and methane in the atmosphere (Houghton et al., 1990).

We know today approximately the amounts of CO_2 that have been emitted into the atmosphere by fossil fuel combustion and changing land use (deforestation and expanding agriculture). We can relate observed increases of atmospheric CO_2 to these human activities. Since a continued increase of the atmospheric CO_2 concentration might lead to changes of the global climate, it is essential to be able to project the likely future concentrations that may occur due to various possible rates of CO_2 emission.

Over the last 100 years or so, information regarding changes of global climate has been quantified on the basis of direct observations. These changes are best characterized by the global-mean temperature (Wigley, 1989). Global-mean temperature changes, based on data from both the land and marine areas of the globe, have shown a trend of warming by at least 0.5 °C over the period of 1958-1989 (Wigley, 1989), which coincides with the increase of CO_2

concentration by about 3-15 percent from 1858 to 1958 (Machta, 1978) and by about 8 percent from 1958 to 1984 (Bolin et al., 1986b). It is also reported (Folland et al., 1984) that a worldwide marine temperature fluctuation between the period of 1856-1981 range about 0.6 °C, with the coldest period being centred around 1905-1910 and the warmest occurring in the 1940s.

For projecting the changes of future global warming due to the greenhouse effect, we must first estimate the future changes in greenhouse gas concentrations which will depend on future population growth, future agricultural activities and practices, future energy production, and deforestation (Barth and Titus, 1984; Wigley, 1989; Houghton et al., 1990). A detailed prediction of future burning rates of fossil fuel would have to be speculative, but the upper and lower limits for this function with some confidence can be indicated. Siegenthaler and Oeschger (1978, p392) reported that "as a lower limit we can assume a constant CO_2 production rate at the level of 1975 --- that is equivalent to 2.4 ppm/year, so that a doubled CO_2 level (to the pre-industrial level) would be reached between the years 2160 and 2480; but as a upper limit, we assume that the production rate of CO_2 grows by 5.0 percent/year, then the CO_2 concentration would be doubled by the year 2020." Zimen (1979, p163) announced a similar result. He indicated that "we could proceed burning fossil fuels as long as the supply lasts without reaching a doubling of the pre-industrial level if the growth rate is kept under 1 percent/year; for a scenario with 3 percent annual increase instead, a doubling of the pre-industrial level will be reached around the year 2040." Bolin et al. (1986b, p xxvii) also summarised that "the upper bound scenario implies that the CO_2 concentration might double by the middle of the next century, while the lower bound scenario implies that doubling of CO_2 concentration will not be reached until after 2100." Recently, Wigley (1989, p6) reported that "the best estimate for the date, at which an equivalent CO_2 level is doubled to the pre-industrial level, is the late 2020s, but it may range anywhere between the late 2010s and the late 2040s."

Recent model studies suggest that the warming for a CO_2 doubling is likely in a range of 1.5-5.5 °C (Manabe and Stouffer, 1979; WCP, 1981; Clark et al., 1982; CDAC, 1983; Washington and Meehl, 1984; Bolin et al., 1986b; Wigley, 1989). For instance, using a three-dimensional spectral atmospheric general circulation model, Washington and Meehl (1984, p9475) indicated that "Globally averaged, the annual mean surface air temperature increase computed over the last 3 years of an integration with a full annual cycle for 2 x CO_2 compared to the control for 1 x CO_2 is 3.5 °C." Wigley (1989, p10) also indicated that "the best estimate given in recent reviews of the greenhouse problem is that the equilibrium global-mean temperature would range between 1.5-4.5 °C with about 95 percent confidence." Under the IPCC Business-as-Usual (scenario A) emissions of greenhouse gases, a rate of increase of global mean temperature during the next century was projected to about 0.3 °C per decade with an uncertainty range of 0.2 °C to 0.5 °C per decade (Houghton et al., 1990). A comparison of the results of recent assessments of the greenhouse problem is summarized in Table 2.2.

Table 2.2. A comparison of recent assessments of the CO_2 problem

Studies	Future atmospheric CO_2 concentration in ppm*	Globally averaged surface temperature response for CO_2 doubling
Manabe and Stouffer (1979)	-	2 °C
WCP (1981)	410-490 in 2025 (most likely 450)	1.5-3.5 °C
Clark (1982)	371-657 in 2030	2-3 °C
CDAC (1983)	428 in 2025 ('best guess')	1.5-4.5 °C
Washington & Meehl (1984)	-	3.5 °C
Bolin et al. (1986b)	380-470 in 2025	1.5-5.5 °C
Wigley (1989)	560 in late 2020s (Equivalent CO_2,'best guess')	1.5-4.5 °C
Houghton et al. (1990)	550 in 2100 (Business-as-Usual)	3 (1.1-5.5) °C

* ppm = parts per million by volume

2.5.2. Greenhouse effect---A rising sea-level

One of the consequences arising from the enhanced greenhouse effect is global warming, and without doubt a rise in sea level. The global warming due to increasing atmospheric CO_2 for example could melt part of the ice sheets over Greenland and the Antarctic (Clark and Primus, 1987) and other small glaciers (Meier, 1984). It will also result in thermal expansion of sea-water (Gornitz et al., 1982; Wigley, 1989; Warrick and Farmer, 1990). Together, they could subsequently raise the global sea-level about one metre (Houghton et al., 1990) or so (Hoffman, 1984) by the end of the next century. It has been indicated that the global sea-level trend for the past century has some similarity to the trend in global surface air temperature (Hansen et al., 1981). Most of the positive correlation arises from the general increase in both sea level and temperature (Gornitz et al., 1982).

From geological data, particularly derived from the IGCP Projects, it has been concluded that sea level has been dramatically changed in the past, for example, since the last glacial (Fairbridge, 1961; Jelgersma, 1961; Mörner, 1971; Tooley, 1978a, 1982; Devoy, 1979; Ota et al., 1981; Bloom, 1983; Kidson, 1982; Hopley, 1983; Shennan, 1982, 1986a,b; Huang et al., 1987a). In northwest England, for instance, Tooley (1978b) indicated that during the eighth millennium, sea-level rose extraordinarily rapidly with a rate of sea-level rise of 35 mm/yr. Tooley (1989, p35) explained "the rapid rates of sea-level rise are undoubtedly associated with the catastrophic melting of the Laurentide Ice Sheet, shortly after 8000 radiocarbon years ago," and pointed out that "Earlier, similar rates of sea-level rise associated with the melting of the Fenno-Scandinavian Ice Cap resulted in the inundation of continental shelves and the severing of land bridges: rates of transgression across the continental shelves ranged from 15 to 60 km per 1000 years, or up to 60 metres per year."

The historic record of marine inundations and damaging storm surges, together with the instrumental record from tide gauges, indicated a rising sea-level of one to two millimetres per year over the past century (Tooley, 1989). In some areas, this rate of rise is increased as the result of land subsidence; in others it is reduced by uplift. For instance, it is (Woodworth, 1987) reported that relative sea-level changes in the years of 1916-1982 were obtained as -1.29±0.22 mm/yr from Aberdeen, while +0.62±0.20 mm/yr from Sheerness, due to the north-south tilting of the British Isles.

Based on records from tide gauges in Amsterdam, Stockholm and Warnemunde, and a method applied to correcting the tide gauge data from the isostatic factor, Mörner (1973) indicated that the eustatic sea-level was relatively static from A.D. 1682 to A.D. 1840. A rise with a rate of 1.1 mm/yr from A.D. 1840 to A.D. 1950 followed. Ekman (1986a) examined the world's second longest series of sea level observations in Stockholm 1774-1984, and concluded that eustatic sea level changes due to northern hemisphere climatic variations since A.D. 550 probably have always kept within -1 and +2 mm/yr, by comparing with the mean temperature curve deduced from ice cores from Greenland. Concluding data from different parts of the world, Gornitz et al. (1982) and Gornitz and Lebedeff (1987) reported that the global-mean eustatic sea-level rise during the past century is 1.2±0.3 and 1.0±0.1 mm/yr, derived by averaging 14 and 11 regional tidal data, respectively. Concerned with similar data, Barnett (1983, 1984) indicated a relatively higher rate, 1.43 ± 1.4 mm/yr from 1881 to 1980, or 2.27 ± 2.3 mm/yr from 1930 to 1980. Recently, a higher rate was given as 2.4 ± 0.9 mm/yr for 1920-1970 (Peltier and Tushingham, 1989, from 40 stations) and 1.7 ± 0.13 mm/yr for 1900-1980 (Trupin and Wahe, 1990, from 84 stations). In China, Chen (1991) examined the changes in sea level at the Yangzhi (Changjiang) River mouth since the early 1920s, with consideration of factors of the recent local tectonic movement, ground subsidence caused by groundwater pumping, and river discharge. He concluded that mean sea-level has been rising at a rate of 1.0 mm/yr, with a faster rise in high tide levels. Ren (1991) investigated records from 31 tide gauges along the Chinese coast and suggested that the eustatic sea-level rise in the past 80 years has been at a rate of 1-2 mm/yr.

For projecting the future sea-level rise, Hoffman (1984, p80) indicated that "future global sea-level will depend primarily on three factors: the total quantity of water filling the oceans' basins; the temperature of the oceans' layers, which determines the density and volume of their waters; and the bathymetry (shape) of the ocean floor, which determines the water-holding capacity of the basins," and "projecting sea-level rise requires the means to estimate future changes in atmospheric composition, to relate these changes to global warming, and then to determine how the warming can cause land-based snow and ice to enter the sea and the oceans to expand thermally." On the basis of the knowledge mentioned above, Hoffman (1984) presented a range of sea-level rise estimates, termed scenarios. In Hoffman's model (1984), factors being mainly considered include the melting of ice sheets over Greenland and the Antarctic and the thermal expansion of ocean water. These scenarios are listed in Table 2.3. and are critically assessed in Chapter VI. In the IPCC report, however, Warrick and Oerlemans (1990) suggested a relatively low estimate of sea-level rise, 66 cm by the end of the next century (best estimate of Business-as-Usual Scenario), based on their calculation mainly concerning the contribution of the thermal expansion of sea water and the melting of small glaciers and the Greenland Ice Sheet. In IPCC's model, the Antarctic would contribute negatively to the rising sea-level (Table 2.4.).

Table 2.3. Estimated sea-level rise (in cm) in the next century (after Hoffman, 1984)

Year	Conservative estimate	Mid-range low	Mid-range high	High estimate
2000	4.8	8.8	13.2	17.1
2025	13.0	26.2	39.3	54.9
2050	23.8	52.3	78.6	116.7
2075	38.0	91.2	136.8	212.7
2100	56.2	144.4	216.6	345.0

Table 2.4. Estimated sea-level rise (in cm), 1985-2030, "Business-as-Usual" Scenario (after Warrick and Oerlemans, 1990)

	Thermal Expansion	Moutain Glaciers	Greenland	Antarctica	Total
High	14.9	10.3	3.7	0.0	28.9
Best	10.1	7.0	1.8	-0.6	18.3
Low	6.8	2.3	0.5	-0.8	8.7

The estimates given above are the mean values of global sea-level rise. Clark and Primus (1987) indicated, however, that the melting or retreat of ice sheets does not result in a uniform rise in observed sea level everywhere, because the observed sea-level change is actually the difference between two dynamic surfaces --- the geoid and the Earth's solid surface. Nevertheless, they reported that if the eustatic sea-level rise caused by the melting of Greenland and Antarctic ice sheets is 100 cm, the local sea-level rise in the Thames Estuary will be 134.2 cm.

2.5.3. Impacts of future sea-level rise

Rossiter (1962b) reported that a sea-level rise of as little as 15 cm may double the probability of damaging storm surges on the east coast and triple on the west coast of Britain. Barth and Titus (1984) indicated that a rise in sea level of one or two metres would inundate low-lying areas and drown coastal wetlands; erode shorelines by hundreds of metres; raise the salinity of rivers, bays and aquifers and increase marine flooding in the coastal lowlands that are now fresh-water regions or residential and commercial regions. However, the impact of projected sea-level rise on the coastal lowlands of the earth was not considered until the 1970s (Shennan and Tooley, 1987).

During the last decade, an assessment of the impact of sea-level rise has been made at two scales: the detailed site scale reported by Barth and Titus (1984) and the global scale analyzed by Henderson-Sellers and McGuffie

(1986). For the same purposes, a simple geographical information system (GIS) has been developed and applied to two high risk coastal lowlands in the United Kingdom: the Tees Lowlands and the Fenlands (Shennan and Tooley, 1987; Shennan and Sproxton, 1990). The GIS integrates readily available data on sea level rise scenarios, land altitudes, and socio-economic variables. In Shennan and Sproxton's study (1990), assessment was first given to the environmental hazard at a local scale and then to the likely impacts on and possible responses from the local societies. Based on the present knowledge, such impact would be at first on the physical environment; consequently on economic development and human activities in coastal lowlands.

In Egypt, El-Raey (1990) indicated that the Nile delta is already eroding by as much as 60 metres per year, due to the construction of barrages and dams across the delta over the last century. He also estimated that the direct inundation from a one-metre rise of sea level, combined with waterlogging and salinization up to (today's) two-metre contour, would destroy one-quarter of the agricultural land on the delta and displace 8 million people. In Bangladesh which is often cited as a major loser to sea-level rise, Ali and Huq (1990) found that the losses due to a one-metre rise would be significantly high with 25,150 km^2 being inundated. In Nigerian delta, Awosika et al. (1990) suggested that a one-metre rise in sea level would aggravate existing erosion, which is currently close to 25 m per year at Lagos Beach. They also indicated that increased flooding would be a particular problem for barrier islands as well as industrial and oil-handling facilities in the delta. In the Pearl delta, southern China, Li (1988) suggested that the whole delta plain would be below the mean sea-level as a one-metre rise in sea level occurs and increase the threat from sea and river floods. In the Northern China Coastal Plain, Han et al. (1991b) indicated that a one-metre rise in sea level would inundate coastal lands of about 20,000 km^2 and affect 9.5 million people. They estimated that improvement of the sea defence systems along the coast (a soil-stone embankment of about 500 km long and 5-6 m high with 1 metre freebroad) would cost at least 91.74 million U.S. Dollars (at 1990 prices), in order to guard against a one in 100 year storm surge. This cost does not include 96.2 million U.S. Dollars which have already been spent to raise embankments in some coastal sectors in northern China during the last decade.

Titus et al. (1984, p19) stated that "the physical consequences of sea-level rise can be broadly classified into three categories: shoreline retreat, temporary flooding, and salt intrusion," and "the most obvious consequence of a rise in sea level would be permanent flooding (inundation) of low-lying areas." In economic terms the commercial and industrial properties already existing on coastal lowlands, such as those in the Tees Lowlands (Shennan and Tooley, 1987; Tooley, 1989; Shennan and Sproxton, 1990) and the Thames Lowlands (International Disaster Institute, 1981), will be damaged by marine flooding in the near future. It is known that a great deal of money has been spent to construct the Thames tidal barrier (some £440 million at 1982 prices) and to strengthen the sea defence systems downstream from the barrier (Some £300 million at 1982 prices) for protecting the properties and life on the Thames lowlands (Gilbert and Horner, 1984). But, will the barrier and the sea defence system be effective in the next century, if sea level rises for over one metre? If not, how much money will still have to be spent to protect those properties in the next century ?

The marine flooding will also damage the agricultural lands on the low-lying areas, such as those in the south side of Morecambe Bay (Tooley, 1989). Titus (1984, p23) warned that "communities and individuals must decide whether to attempt to protect themselves from the consequences of sea-level rise or adapt to them," and "generally, prevention will be economically justifiable only at valuable locations, such as population centres, defense installations, historical sites, and areas of environmental importance, ... other areas would have to adjust to the consequences." To help people make their decision before the consequences of sea-level rise are to be met, an 'early warning system' must be established as early as possible to provide options to the communities and individuals who are living and occupying the coastal lowlands (Shennan and Tooley, 1987).

CHAPTER III

TECHNIQUES EMPLOYED

As usual, some conventional techniques for sea-level studies such as levelling, sampling, stratigraphic analysis, pollen analysis, diatom analysis, and radiometric analysis are used in the current study to reconstruct the history of Flandrian sea-level changes. The data and results are stored in databases, and are plotted in diagrams by a computer. A new method, the Geographical Information Systems (GIS) developed in the Department of Geography, University of Durham, has been successfully employed in the investigation of the impact of predicted future sea-level rises on the coastal lowlands. These techniques were learnt during the current three-year course and are outlined below, together with survey of the experiences obtained from the study.

3.1. Field Work

3.1.1. Levelling

The altitudes of the stratigraphic surveying and sampling sites were obtained, using a Kern Automatic Level, **GKI-AC**. There is a local benchmark 450 m south to the Bore 6 and is marked on a corner of a farm house, High Frith, near the road. The position and altitude of this benchmark were obtained from the Ordnance Survey Bench Mark Lists. Therefore, all measured altitudes are related to Ordnance Datum (Newlyn), which is the zero datum of the United Kingdom and is equivalent to the average value of mean sea-level at Newlyn, Cornwall, for the six-year period 1915-1921 (Tooley, 1978a). A temporary benchmark was set up near Bore 4 for saving working time and reducing survey error. The temporary benchmark was first levelled to the local benchmark and then all the boreholes were levelled to the temporary benchmark.

The distances between reading points and staff points were kept shorter than 100 m, in order to keep the survey error as low as possible. Some of the levelling were carried out under windy or rainy conditions, which produced a maximum survey error of $\pm$0.20 cm over a distance of 100 m. The lowest survey error was $\pm$0.02 cm over the same distance. Therefore, the average survey error among the boreholes is calculated to be $\pm$0.08 cm. The range of altitudes from Bore 0 in the landward end to Bore 10 in the seaward end (see Figure 4.5.) is 3.8 m over 1.8 km. The maximum altitude range measured between Bore 2 and Bore 11 is 4.52 m.

3.1.2. Sampling

In this study, four traditional samplers: Gouge sampler, Russian-type

Sampler, Piston Corer and Monolith Tin, were employed to retrieve samples from depths the stratigraphy was recorded and to get samples for laboratory analysis. The ways of using these samplers are outlined below.

The **Gouge Sampler** is the one used most frequently in work investigating the stratigraphy of the site. It is an open-chamber sampler with a diameter of 2.5 cm and a length of 1 m, associated with extension rods of 1 m length for obtaining deeper samples, usually as deep as 10 m. The use of the sampler is very simple. It should be put vertically into the ground by hand with a T-shape handle, and is rotated through 360° when the required depth is reached. Then it is lifted out vertically. Depending on the angle, non-vertical use of the sampler may raise errors in depth up to 0.04 m (Shennan, 1982). After the sampler is lifted out, the face of the sediments contained within the chamber is cleaned, and the stratigraphic layers are measured and recorded. However, it must be noted that the very wet and soft materials are difficult to extract from the ground. Stiff or sticky materials from the upper strata could be retained within the chamber of the sampler and impede the extraction of soft materials from the lower strata required. These disadvantages of the Gouge Sampler could be misleading as to the positions of the strata during recording of stratigraphy of the borehole taken. This problem occurred when Bore 1 and Bore 2 were taken. Resamplings were made at points 10 cm from the original boreholes, whose original readings became invalid.

The **Russian-type Sampler**, first described by Jowsey (1966), can be used either for stratigraphic investigation, or for getting samples for laboratory analysis. The sampler is composed of an anchored fin and a movable sampling chamber of 50 cm by 5 cm in size, which can be rotated through 180° against the fin. Thus, the Russian-type Sampler can only obtain a semi-cylindrical core of sediment. Also, the sampler employs extension rods of 1 m in length for getting deep samples. The use of the sampler is quite similar to that of the Gouge Sampler. It is put into the ground vertically, and rotated through 180° against the anchored fin as soon as the required depth is reached, which means that the sediments wanted are enclosed within the chamber. Then, it is pulled out and the handle turned in the opposite direction, so that the sediments enclosed can be recovered. Finally, the sediment is transferred to a half-diameter plastic pipe and sealed in polythene. The pipe containing the sediment is sent to the laboratory. The sediments sampled by the Russian-type Sampler are much less disturbed because the sampling chamber is closed until the required depth is reached. The sediments obtained are enclosed until they are transferred to the pipe, so that these samples can be used for pollen and diatom analyses, and sometimes for radiocarbon dating. In the present study, the Russian-type Sampler was used at the same place of PIT2 to obtain deeper samples.

The **Piston Corer** used in the present work consists of a movable piston in an open-ended sampling tube of 1 m by 4.8 cm diameter (Merkt and Streif, 1970). The corer can be used for getting large and disturbed samples. Using a vibrator, the sampling tube is plunged into the ground; when it reaches the required depth for beginning sampling, the piston is held in place by a wire which links with the piston. The sampling tube is pushed down until the piston reaches the top of the tube, e.g., the samples wanted are completely within the tube. Then, the tube is removed from the ground by a jack. The ends of the tube are sealed with polythene for transportation to the laboratory. In the laboratory, the samples can be removed from the tube by an extractor which pushes the samples out into a half-diameter plastic pipe, which is then sealed and stored in a refrigerator. Before the corer is used for sampling, a preliminary investigation on site is necessary to be carried out by the Gouge Sampler, because the piston can easily open too early and so unwanted samples would be obtained. It can also open too late, and the required sample would be missed. The other disadvantage of the corer is that the samples obtained can be compacted either during sampling or extraction, which leads to a reading of incorrect depths of the samples. This type of corer was used for getting the samples of PC-1 borehole in the current study.

The **Monolith Tin** is an one-side-opened metal box with dimensions of 50 cm (or 25 cm) by 10 cm by 10 cm. Monolith Tins can be used for sampling from free-face excavations. Before sampling, the face of the profile where it is required for sampling must be cleaned using a spatula or trowel. The Monolith Tin can be pushed in by hand or rammed by hammer into the sediments. When dug out, it contains the sampled sediment, which is then sealed in polythene.

The Monolith Tin can obtain a large amount of samples which are useful for detailed stratigraphic analysis and pollen, diatom analyses, and for radiocarbon dating. Samples were taken by Monolith tins in PIT1 and PIT2 in this work.

3.1.3. Stratigraphic analysis

The quality of the interpretative evidence, upon which environmental reconstruction is based, is as accurate as the quality of the stratigraphic data collected in the field (Tooley, 1981). As to the stratigraphic study, it must be initially carried out by carefully measuring the depths of each boundary between layers; to label them in centimetres from the top of the borehole taken, and to assign numbers for the layers from the base upwards.

In the stratigraphic study, employing a universally-used descriptive scheme for recording the components of a deposit layer in a stratigraphic sequence is very important. This allows it to be comparable to the data obtained by the other researchers (Tooley, 1978a). In the present study, every deposit layer in the boreholes obtained was specified using **Troels-Smith's scheme** which defines three elements: the components, the humification degree of the in situ organic materials, and the physical properties of the layer (Troels-Smith, 1955).

Besides using the symbols defined by the Troels-Smith scheme to specify layers, it is necessary to give a short written description of the nature of a layer seen in the field. In summary, the stratigraphic recording in the field comprises measuring depths, specifying components, humification, if applicable, and physical properties, and descriptive nature of the layers in a borehole.

In **Troels-Smith's Scheme**, the first element to be described is the components of a layer. Seventeen component parts are specified within the scheme. A layer may contain one or more components, the proportions of which are estimated on a 25 percent basis on a scale of 1 to 4, with 1 indicating 25 percent composition of component and 4, 100 percent. The slight presence of a component is indicated by a plus sign in the final formulation.

Turfa is defined as the roots of woody and herbaceous plants, and the stumps, trunks, branches and stems if connected to the roots, as well as mosses. Hence turfa means the sediments which have been deposited in situ. **Detritus** is made up of plant fragments which are unconnected to a root system, and composed of fragments of wood, bark, branches, and trunks, stems and leaves, fruits and seeds, all of which have either rained down onto the forest floor or have been washed into the site, then deposited. **Limus** is made up essentially of small organic particles arising from the productivity of lakes and the input of organic and inorganic materials from the drainage basin. Sometimes, the Limus detritus (Ld) is too difficult to distinguish from the **Substantial humosa** (Sh) by the naked eye in the field. They may, however, be distinguished after pollen and diatom analyses, because there are usually a great number of aquatic pollen and diatoms within the Ld sediment as opposed to Sh sediment. Argilla is minerogenic sediment and characteristically sticky or plastic. Grana is the sediment of macroscopic particles.

Humification of the organic materials is estimated on a five point scale in Troels-Smith's scheme. 0 on the scale indicates that the plant structure is unhumified and 4 indicates more or less complete humification. The number of the scale can be labelled on the upper-right corner of the component mark in order to indicate that a humification degree has been estimated.

The physical properties of a layer include the degree of darkness (nig. = nigror), stratification (strf. = stratificatio), elasticity (elas. = elasticitas), and dryness (sicc. = siccitas) of the sediments in the layer, which are all estimated on a five point scale. In addition, the sharpness of the upper boundary of a layer is specified in most cases on the scale lim. 4 acute, to lim. 0 diffuse (Tooley, 1978a).

The depth, components, degree of humification, and physical properties of a layer may be summarized in an abbreviated form, associated with a short written description. For example, the complete description of the Stratum 3 of PIT1 is shown as:

Layer	Depth (cm) (Altitude m.)	Description
3	193-236 (5.234-4.804)	Th(Phrag.)^{2}4, Dl+, Tl^3+. nig.2, strf.0, elas.2, sicc.2, lim.0. light yellow, slightly humified roots and stems and fragments of Phragmites with birch branches and woody roots.

Some problems of using the Troels-Smith's Scheme during the present study were found. First, it is difficult for an investigator in the field to judge precisely the proportion of one component which may be over- or under-estimated. The investigator would be in a dilemma to record the component on a 25 percent basis if the proportion of this component is about 40 percent for example. Second, in some cases, roots of some plants could penetrate the underlying stratum. Therefore, these roots were recorded in the stratum below rather than in the stratum associated with the branches and stems connected to the roots.

After the layers of a borehole are described by the method indicated above, the stratigraphic data obtained can be stored in a database file, and the borehole or a transect with the other boreholes can be plotted out from the output of a computer using the program which is available in the Department of Geography, University of Durham. The computing techniques used in this study will be introduced later in this Chapter.

3.2. Laboratory analysis

3.2.1. Pollen analysis

Pollen (here and subsequently 'pollen' means pollen grains from angiosperms and gymnosperms or spores from pteridophytes or both, according to the context) analysis is a useful tool to investigate the vegetational history, to determine the indicative meanings of sea-level index points which will be employed to reconstruct the history of sea-level changes and as a crude chronological tool. The basic pollen analysis has borrowed from cytology and genetics, morphology, physics, chemistry, and other branches of science, even mathematics, all of which provide a valuable basic knowledge for its application. Pollen has some useful features which prove valuable as indicators of conditions in the past (Moore and Webb, 1978). For instance, they are preserved much more easily than many other parts of plants, due to their structural chemistry. Their structures and sculpturing may be a highly recognizable object, which means that the identification can often be taken to the species level. Their abundance within many sediments allows a quantitative recording of the various types to be made (Moore and Webb, 1978). Because of these features, the applications of pollen analysis may include: tracing the history of plant groups and species; tracing the history of plant communities; dating deposits; studying climate history. The present study employs just this technique, pollen analysis, for the reconstruction of Flandrian environmental changes and of the tendency of Flandrian sea-level changes in the site.

It must be noted that some pollen grains and spores could not be identified to the genus and species levels in the current study, such as Gramineae, Cyperaceae and Filicales, so that interpretation for these in terms of depositional environment is slightly difficult. However, it should be borne in mind that the nature of the sediments from which pollen samples are collected, shows that some of the pollen grains and spores can possibly be assigned to species levels. For example, the pollen grains of Gramineae from the lower part of PIT1 could be related to the species of <u>Phragmites</u> which is the dominant peat-forming plant in the deposit in that section. Also, spores of Filicales, which have been identified from many samples in the current study, are normally bean-shaped with a furrow, sometimes with a plain shiny bean inside, but their outer covers are usually lost in many Filicales except <u>Polypodium</u> when they became fossilized (Andrew, 1984). Most species of Filicales live amongst rocks, on trees, and high-ground grasses, but <u>Dryopteris spinulosa</u> lives in wet woods, marshes and wet heath (Clapham <u>et al.</u>, 1959). In the current study, over 95 percent of Filicales spores are identified from samples which come from either <u>Phragmites</u> turfa or saltmarsh organic substance (brackish limus). Therefore, these spores could probably belong to, or could be related to, the species <u>Dryopteris</u> <u>spinulosa</u>. Other ferns with similar habitats are: <u>Lycopodium</u> <u>inundatum</u>, damp peaty lowlands; <u>Selaginella selaginoides</u>, damp mossy and grassy places; and <u>Polypodium</u> <u>vulgare</u>, often on trees, common in wet districts (Clapham <u>et al.</u>, 1959).

For the objectives of the study, pollen analysis was used for assessing the relative chronology of the deposits and elucidating the local changes in vegetation associated with the changes of sea-level. Two hundred grains of land pollen were counted for each level, except for the lower organic layer in which pollen preservation is not good. Pollen gains counted were classified into four life-form groups: trees, shrubs, herbs and aquatics, and one taxonomic group: spores. The frequencies of each taxon of tree pollen were calculated as percentages of total tree pollen, whilst those of shrub and herbaceous pollen were calculated as percentages of total land pollen. The frequencies of aquatic pollen and spores were calculated as percentages of total pollen. The enumeration and plotting is carried out by using a computing (Tilia) programme in the Department of Geography, University of Durham.

3.2.2. Diatom analysis

The study of diatoms in Britain was first introduced by W. M. Smith in his publications, 'The Synopsis of British Diatomaceae' in 1853 and 1856. Smith's two volumes contain descriptions of 466 species of diatoms, of which 224 are brackish or marine. The other important contributions to the study of the subject in Britain are: 'A Preliminary Check-List of British Marine Diatoms' by N. I. Hendey (1954), who collected all the published records and added his collections to compile this list which contained 771 species arranged in 104 genera; and 'An Introductory Account of the Smaller Algae of British Coastal Waters. PART V: Diatoms', also by N. I. Hendey (1964). He introduced an account of the life history, reproduction, structure, classification and distribution of the more frequently occurring diatoms to be found in the open sea, in coastal water, in estuaries and on mud-flats or salt marshes around the coasts of Britain.

Diatom assemblages which are often found in cores of fine-grained coastal sediment can accurately record the changing salinity of the local environment. Diatoms are useful for sea-level study because they are widespread in natural aquatic environment; many species prefer specific salinity conditions; the silica constituting the valves in relatively resistant to chemical alterations after burial; and diatoms are often preserved with radiometrically dateable carbonaceous material (Plamer and Abbott, 1986). Since publication of the earliest diatom literature in the 1980s, the distinction between marine and non-marine habitat preferences has been recognized. Today, many diatom species can be classified according their salt-sensitivity as marine (greater than 30 parts per thousand salinity), Brackish (2-30 parts per thousand salinity), fresh water (less than 2 parts per thousand salinity), and halophobes (Jin et al., 1965, 1982; Round, 1971). Diatoms may be free-floating (planktonic) or attached to a substratum (benthonic) (van de Werff and Huls, 1958-66). Diatoms vary greatly in size, the smallest being 4 or 5 micrometres in diameter or length, while the largest exceed 1 mm (Jin et al., 1982). Most British marine diatoms vary between 40 and 200 micrometres in diameter or length (Hendey, 1964).

Hendey's book (1964) was the main reference to identifying and counting the diatoms during the present study. The classification of Jin et al. (1965, 1982) was also used as a reference. A cross-check of synonyms has been made to Harley (1986) (see Appendix III).

There are two ways to summarise the results of diatom counts. One is to sum up the number of the species identified and the percentages of each species group which shows salinity, and to interpret the salinity of the deposit medium (e.g. marine water or brackish water). In this way, the number of diatoms within a species need not be counted, so that it is an easy and quick way of diatom analysis. But, it must be noted that this way is not appropriate where one or two species are dominant in a diatom assemblage, or if a diatom assemblage is composed of only a few species of diatoms (Huang et al, 1987b). Therefore, the other way is to sum up the percentages of each species of diatoms obtained, and to interpret the sedimentary facies. In this way, each individual (valve) diatom needs to be counted.

3.2.3. Sampling for radiocarbon dating

In the last forty years there has been a remarkable growth in the number of techniques made available for dating Quaternary sea-level change. Amongst those, radiocarbon dating, when allied to the more traditional forms of relative dating, such as pollen analysis, has permitted the determination of complex histories of sea level in the period following the last glacial maximum (Sutherland, 1987). This technique has been used with great confidence. It should be indicated that the degree of resolution possible in studies of former sea level is primarily a function of the degree of preservation and accessibility of field evidence. The objective of dating a particular sea-level event is more reliably achieved if more than one technique is applied, thus permitting cross-checks on the age of the event (Sutherland, 1987). In the present study, radiocarbon dating has been used as the principal method applied in tracing the changes of sea level, in association with independent relative dating derived from the analysis of local and regional pollen assemblage zones, while integrating the local sedimentary sequence into regional stratigraphy. These relative dating relationships may serve as a direct check on the accuracy of local radiocarbon dates.

In order to interpret the evidence of sea-level changes accurately, the sampling for radiocarbon dating in the present study was undertaken in three stages. At first, the local stratigraphies are established with a detailed stratigraphic survey; analysis of diatoms from the minerogenic layers, and of pollen grains from the organic layers. The results of this stage provide knowledge of the local coastal sedimentary sequences. The second stage is to examine minerogenic/organic contacts more closely, and give an assessment of indicative meaning to each contact, from which immediately above or below, a sample should be selected for radiocarbon dating. To avoid possible contamination from younger rootlets and detrital old carbon, is the third procedure. during which a detailed assessment of the samples to be selected for radiocarbon dating is made.

3.3. Computing

Computing techniques have been applied to the present study for handling, analyzing and displaying the data obtained from field investigations, laboratory analyses and published literature. Computing packages of dBASE III, DOGGS, pc-ARC/INFO, GIMMS, and others available in the Department of Geography, University of Durham have been applied in the present study.

3.3.1. Data management and analysis

The data obtained from stratigraphic surveys, the counting of pollen grains and diatoms, radiocarbon dating, and reference of literature can be stored in databases on computers using dBASE III package. These data can be easily displayed, changed, found, rearranged, analyzed, related and printed from databases. A database is an organized collection of related information or data which could be applied to most research topics. In a database file, all the data for a particular entry is called a record, and each item of information within a record is called a field. Before putting data into a database file, its structure must be defined. The structure of a database file includes the names of fields under a record, the number of characters in a field, and the type of information. In practice, a database file can store information on character, numeric data, date, logical data and memo data. In the present study, databases of record structure are used to store data of stratigraphy, pollen, diatom, radiocarbon dates and others. This kind of database structure can easily be arranged to store a one-dimensional array of fixed or variable length, and divide data into a number of equal partitions. In a stratigraphic database, for instance, the information on a borehole is stored as a record, each sedimentary layer of the borehole is defined as a field, each field is divided into a number of columns, and each column stores one of the characters of the sedimentary layer.

By applying the pc-ARC/INFO package, data for spatial study of impact of future sea-level rises is obtained and digitised from various maps. It is then stored in the databases of relational database structure, which contain an ordered set of attribute values that are grouped together in two-dimensional tables. Each table (or relation) is usually a separate file, containing attribute values that are related to the specified features such as the points, lines and polygons. The relational databases have a great advantage that their structure is very flexible and can meet the demands of all queries formulated using the rules of Boolean logic and mathematical operations (Burrough, 1986). The disadvantage of relational databases is that many of the operations involve sequential searches through the files to find the right data to satisfy the specified relations. This can involve a considerable amount of time with large databases, even on fast computers.

Statistical analysis of data is available in the Department by applying the DOGGS package which is an integrated, menu driven statistical and graphical package suitable for the numerical analysis and display of geographical data. For instance, in this thesis, the principle component analysis for the pollen assemblages and the dissimilarity analysis of neighbouring levels of pollen diagrams were carried out by applying the DOGGS package.

3.3.2. Geographical Information Systems

In recent decades, Geographical Information Systems (GIS) have been developed to be a powerful set of tools for collecting, storing, transforming, and displaying spatial data from the real world for a particular set of purposes. Geographic data describe objects from the real world in terms of their position with a known coordinate system, their attributes that are unrelated to position, and their spatial interrelations with each other (topological relations). The GIS differ from computer graphics because the latter are largely concerned with the display and manipulation of visible material. The GIS should be thought of as being very much more than means of coding, storing, and retrieving data about aspects of the earth's surface (Burrough, 1986). Because these data can be assessed, transformed, and manipulated interactively in a GIS, they can serve as a test bed for studying environmental processes, or for analyzing the results of trends of environmental change.

Unlike many other kinds of data, geographical data are complicated by the fact that they must include information about position, possible topological connections, and attributes of the objects recorded. Geographical data are very often recognized and described in terms of well-established geographical phenomena. All geographical data can be reduced to three basic topological concepts: the point, the line, and the area plus a label saying what it is.

A map is usually represented in two dimensions. However, because each cell in a two-dimensional array can only hold one number, different geographical attributes must be represented by separate sets of arrays, known as 'overlay'. Therefore, each separate attribute should be stored in, or digitized into a separate coverage, such as the coverages of the 2 m Spot Height, the 5 m Contour, and the Landuse classification. These attributes may be qualitative (such as landuse classes) or quantitative (such as population density). In GIS, similar to conventional mapping, both qualitative and quantitative information can be expressed as areas of equal value separated by boundaries. Quantitative data can also be mapped by assuming that the data can be modelled as a continuous surface that is capable of mathematical description. The variations are then shown by isolines or contours (like the 5 m contour).

A GIS has advantages which could avoid the disadvantages of conventional mapping. Burrough (1986) explained that for a paper map, first, the original data had to be greatly reduced in volume, or classified, in order to make them understandable and representable; consequently, many local details were often filtered away and lost. Second, the map had to be drawn extremely accurately and the presentation, particularly of complex themes, had to be very clear. Third, the sheer volume of information meant that areas that are large with respect to the map scale could only be represented by a number of map sheets. Fourth, once data had been put into a map , it was not cheap or easy to retrieve them in order to combine them with other spatial data. Fifth, the printed map is a static, qualitative document. It is extremely difficult to attempt quantitative spatial analysis within the units delineated on a thematic map without resorting to collecting new information for the specific purpose in hand.

3.3.3. The digitised databases

In the present study, the geographical information systems of the areas of Morecambe Bay and the Thames Estuary have been established by using the pc-ARC/INFO package. These systems comprise information of topography, landuse, agricultural classification, and communication. The databases of the ward boundaries and population which were held in the GIMMS have also been applied to assess the impacts of the projected sea-level rise on the coastal lowlands.

The data or information applied to establish the GIS come from sources listed in Table 3.1. Data input and the establishment of the GIS goes through the following procedures:

(1) tracing the specific features (points, lines and polygon boundaries) from a paper map on to a transparency;
(2) digitising the features from the transparency into a computer digitised coverage;
(3) transforming the coordinates of the map on to the coverage;
(4) assigning attributes to the features of the coverage.

Qualities and errors of the GIS (or the coverages) established can be defined in the following ways:

I. Errors from original source

(1) Age of the maps. For instance, the map SD 36/46, which is applied to the altitudinal databases, was surveyed in 1955-1970 and revised for significant changes in 1976, which means that the data were collected some twenty years ago. Even the new maps published in the 1980s, for example, the map SD 45/55 was compiled from 1/10,000 maps which were made from surveys dated 1956-1979, but was revised for significant changes and published in 1984. It is clear that the altitude of some coastal lowlands has changed due to the drainage and sedimentary consolidation since the data were collected. It should also be indicated that the land-use information from the maps was collected from the late 1970s to the early half of 1980s, therefore some recent changes in land-use type and extent could have been included in the coverages digitised.

(2) Scale of the maps. In practice, a map on the scale of 1/25,000 could has a sufficient detail of information, for example in landuse type, for a area covering over 1000 km^2 (Morecambe Bay area, 2400 km^2 and the Thames Estuary, 4400 km^2). Indeed, large scale maps may contain much detailed information, therefore maps of scale 1/10,000 are applied to establish the GIS for the pilot areas, such as Skelwith Pool, Heysham and Morecambe, and Canvey Island, which cover less than 20 km^2.

(3) Metric system. On the metric maps, there are normally contour lines at 5 m intervals, such as the 5 m, 10 m and 15 m contours. However on the maps of

Table 3.1. Data sources of the GIS databases established

Name of the Digitised Database	Scale of Original Map	Date of Publication	Status
Altitudinal databases (MHW, Contours, etc.)	1/25,000(O.S.)	1974-1977 1978-1987	Imp. metric Metric
Land-use databases	1/25,000(O.S.)	1974-1977 1978-1987	Imp. metric Metric
Communication databases (Railway and Roads)	1/50,000(O.S.)	1974-1986	Metric
Agricultural databases	1/250,000	1983 (1)	
Geological databases	1/250,000 1/625,000	1980 (2) 1957 (3)	Lake District The Thames
Quaternary Sediments	1/625,000	1977 (4)	
Pilot area databases (Skelwith Pool, Heysham-Morecambe and Canvey Island)	1/10,000(O.S.)	1976-1985	Metric

(1) Agricultural Land Classification, the Ministry of Agriculture.
(2) Lake District, Institute of Geological Sciences.
(3) Geological Map of the British Islands, Geological Surveys.
(4) Quaternary Map of the United Kingdom, the Institute of Geological Sciences.

Table 3.2. Topographic maps of Morecambe Bay (from Ordnance Survey, Southampton)

Code	Type	Date*	Location	LL / UR
Scale 1:25,000				
SD 49/59	True Metric	1983	Windermere	340 490/360 500
SD 28/38	True Metric	1982	River Leven	340 480/360 490
SD 48/58	True Metric	1981	River Kent	340 480/360 490
SD 17/27	Imp. Metric	1977	Barrow	310 470/330 480
SD 37/47	True Metric	1978	Leven and Kent	330 470/350 480
SD 57	True Metric	1979	Carnforth	350 470/360 480
SD 16/26	True Metric	1977	Walney Island	310 460/330 470
SD 36/46	Imp. Metric	1977	Heysham	330 460/350 470
SD 56	True Metric	1982	River Lune	350 460/360 470
SD 34/35	True Metric	1983	Fleetwood	330 440/340 460
SD 45/55	True Metric	1985	Lune Estuary	340 450/360 460
SD 44/54	True Metric	1983	Pilling Moss	340 440/360 450
SD 32/33	Imp. Metric	1977	Blackpool	330 420/340 440
SD 43/53	Imp. Metric	1977	Kirkham	340 430/360 440

* The date of publication for the maps.

Table 3.3. Topographic maps of the Thames Estuary
(from Ordnance Survey, Southampton)

Code	Type	Date*	Location	LL / UR
TQ 06/16	True Metric	1978	Richmond	500 160/520 170
TQ 07/17	True Metric	1984	Heathrow	550 170/520 180
TQ 27/37	True Metric	1979	Central London	520 170/540 180
TQ 28/38	Ture Metric	1983	Central London	520 180/540 190
TQ 29/39	True Metric	1978	North London	520 190/540 200
TQ 47/57	True Metric	1979	Central London	540 170/560 180
TQ 48/58	True Metric	1979	North London	540 180/560 190
TQ 66/67	True Metric	1989	River Midway	560 160/580 170
TQ 67/77	True Metric	1983	Gravesend	560 170/580 180
TQ 68/78	True Metric	1981	South Essex	560 180/580 190
TQ 69/79	True Metric	1987	Rochford	560 190/580 200
TQ 86/96	Imp. Metric	1976	Sittingbourne	580 160/600 170
TQ 87	True Metric	1983	Isle of Grain	580 170/590 180
TQ 97/TR 07	Imp. Metric	1976	Isle of Sheppey	590 170/600 180
TQ 88/98	Imp. Metric	1976	Southend	580 180/600 190
TQ 89/99	Imp. Metric	1977	River of Crouch	580 190/600 200
TR 06/16	True Metric	1978	The Swale	600 160/620 170
TR 08/09	True Metric	1981	Foulness	600 180/610 200

* The date of publication for the maps.

imperial metric, the altitudinal information was surveyed about the end of the 1950s and the beginning of the 1960s, and used feet as the altitudinal unit. When they were converted to the metric system, the 25 and 50 feet contours were converted to be 8 m and 15 m contours with rounding errors (i.e. 25 feet = 7.6 m). Due to such dis-unification, it is impossible to trace a comparable contour line at either 5 and 10 m or 8 m. Therefore, the present work involves cross-checking of all the available spot heights from the one-kilometre sheets, interpreting 5 m and 10 m contour lines on the imperial maps, then tracing them onto the transparencies.

II. Errors arising through data processing

(1) Transformation of data. It is shown that the establishment of a GIS needs to be undertaken on at least two occasions of data transformation, tracing

information from an original paper map to a transparency, then digitising it to a computer coverage. With this procedure, errors arise from deformation, expansion and contraction of the paper maps; and also from tracing and digitising of data from maps (i.e. the line thicknesses on the transparencies that were then digitized). However, these errors can not be quantified during the present study.

During transforming the coordinates, a Residual Mean Square (RMS) error is calculated. A low RMS error (less than 0.003) is acceptable. In the present work, the RMS errors of the altitudinal, land-use, and the pilot area databases are calculated on a range from 0.00126 to 0.00928. However, those of the agriculture and communication network databases are from 0.00276 to 0.0232. It seems that this sort of error is also affected by the scale and the quality of the paper maps.

(2) Classification and definition of the data. For instance, the classification, definition and interpretation of landuse data from an Ordnance Survey map largely depend on the theme of the study. The accuracy of the landuse types and their boundaries is largely affected by the experience of the interpreter (myself).

These are the likely error sources the present study has met. However, it was not possible to calculate the magnitude of the error at this stage (Burrough, 1986). Fortunately, it is clear that the magnitude of error which emerged in the present study seems not to affect the value of the results of the study, because the aims of the study are focused on the physical impacts of the future sea-level rise on the coastal lowlands rather than the commercial measurement and the engineering designations, and also because the error bands of future sea-level rise are great, i.e. the difference between the low and high estimates of future sea-level rise by the end of the next century is over one metre (Hoffman, 1984; Robin et al., 1986b) and at least 50 cm (Warrick and Oerlemans, 1990).

CHAPTER IV

STRATIGRAPHIC INVESTIGATION IN MORECAMBE BAY

In this chapter, the previous works are to be reviewed. Following this, results of present stratigraphic survey, pollen and diatom analyses, and radiocarbon assay are introduced. On the base of these studies, a Flandrian stratigraphic al model for Morecambe Bay is established.

4.1. Quaternary History

It is difficult to choose a starting point for chronology when examining the Quaternary history of the Morecambe Bay area, because in this area there is no unequivocal evidence for any deposits and landforms older than the last glacial age, the Devensian (Tooley, 1987b). But the literature contains many references to deposits and landform that may pre-date the Devensian Stage (Kendall, 1881; Evans and Arthurton, 1973; Huddart et al., 1977; Pennington, 1978; Tooley, 1987b). Therefore, this section first examines the pre-Devensian evidence for the deposits and landforms, then the Devensian and Flandrian.

4.1.1. Pre-Devensian deposits and landforms

Tooley (1987b, p28) indicated that "basal till units in Low Furness from 0.9 to 5.4 m thick may be Wolstonian cold stage deposits and are overlaid at Lindal Cotes by a persistent organic stratum. This stratum attained a maximum thickness of 7.3 m, attenuating in a north-easterly direction to 1.5 m, and was overlaid by a 23 m thick upper till." Huddart et al. (1977) also illustrated that this organic stratum is regarded tentatively as Ipswichian but an attempt to relocate it by an IGS borehole proved negative. However, the pollen from organic layers in silts beneath a till at Scandal Beck seem to be Ipswichian.

Marine erosion features around Morecambe Bay that may be of Ipswichian age (Tooley, 1987b) include wave-cut notches at altitudes of +4.9 to +5.4 m O.D. and an abrasion platform up to 35 cm lower, measured by Oldfield (1960a) but assigned by him to the time of the maximum post-glacial transgression of the Flandrian Age. Possible sea caves, benches and water-eroded notches in the Carboniferous Limestones around Morecambe Bay have been described by Ashmead (1974) and Tooley (1987b) with altitudes ranging from 12 to 30 m. At Whitbarrow, there are notches at 30 m; Kirkhead Cavern lies at 30 m; and Edgar's Arch or Great Chapel on Humphrey Head also lies at 35 m with a blow hole extending from the back of the cave 12 m higher on a west-facing slope on the headland. Tooley (1987b, p29) indicated that "This altitude is closer to the value of +23 m O.D. given by West (1972, 1980) for the maximum sea-level altitude in late Hoxnian times" and therefore "these erosional and solutional marine features are more likely to belong to the Hoxnian interglacial age."

The pre-Devensian history in and around Morecambe Bay, therefore, can be summarised as follows: (1) There are not any deposits and landform, which are older than Hoxnian Age, found in the area around Morecambe Bay; (2) During the Hoxnian interglacial stage, the sea-level was 27 m higher than the present (West, 1972, 1980), forming a series of erosional marine features at altitudes from +12 to +30 m O.D.; (3) A unit of glacial sediments or till deposited in Low Furness and on the floor of the Irish Sea during the Wolstonian glacial stage; (4) Sea-level rose to +7.5 m O.D.(West, 1972, 1980) during the Ipswichian interglacial stage, and a unit of organic sediments deposited subsequently and overlaid on the Wolstonian Till.

4.1.2. Devensian deposits and landforms

Distributions of the typical tripartite sequence (Upper Till, Middle Sands and Gravels, and Lower Till) around Morecambe Bay were first mapped over 100 years ago (Mackintosh, 1869). However in the Furness area, Aveline (1873) recognised only a Boulder Drift and a Sand and Gravel Drift. Later, Grace and Smith (1922) suggested two drifts in the same area, the Irish Sea Drift and the Local Drift. Huddart et al. (1977) identified two distinct glacial phases in Furness area, expressed by an upper and a lower till, separated by fluvio-glacial sands and gravels. In Morecambe Bay, Knight (1977) recognised only a single till unit up to 55 m thick and overlaid by clays, silts, sands and varved clays, interpreted as complex sedimentation in a sandur plain with freshwater post-glacial lakes. After a detailed investigation, Huddart et al. (1977, p130) indicated that "Both tills are basal, but they are distinguished by the sand/matrix ratios and by lithology. The sand/matrix ratio of the lower till is 0.792 whereas that of the upper till is 0.513," and "The lower till is lithologically composed of a higher percentage of Borrowdale Volcanic Series rocks, Lower Palaeozoic grits and Carboniferous Limestones, with a source from the southern Lake District. The upper till contains erratics from the Western Lake District and Irish Sea basin." As Huddart et al. (1977) suggested, in the area, the lower till can be named as the Main Glaciation Basal Till; the upper till as the Scottish Readvance Basal Till. Hence the western part of Morecambe Bay was affected by Irish Sea ice. The majority of the Bay was affected by Lake District ice. Furthermore, during the Devensian, the Lake District must have nourished a local ice cap and valley glaciers must have pushed into the valleys now beneath Morecambe Bay.

At the maximum of the last glaciation, ice from the southern part of the central Cumbrian massif extended as far west as the Cumbrian lowlands, where it came into contact with Irish Sea ice, as far east as the Lune valley, where it came into contact with the Yorkshire Dales ice, and at least as far south as Low Furness where the ice again came into contact with Irish Sea ice (Gale, 1985). As a result of converging ice streams from these local ice drifts (also from those in southwest Scotland, Ireland and Wales), a large ice stream - the Irish Sea Glacier - was formed (Eyles and McCabe, 1989). The maximum Late Devensian limit of the Irish Sea Glacier at the southern end of the Irish Sea basin was suggested (Bowen et al., 1986) at latitude 50°30' N, which occurred about 22,000 B.P. (Bowen and Sykes, 1988).

The growth of such a large ice stream could impose a substantial load on the earth's crust which becomes downwarped. The amount of isostatic deflection caused by the ice load is in part controlled by the density of ice and displaced mantle materials but it is also a function of the length of the crustal flexural parameter (Walcott, 1972). Using an estimated maximum ice thickness of 2000 m, crustal flexural parameters of 50-200 km and densities of 0.9 and 3.37 g/cm^3 for ice and mantle materials, Andrews (1973) estimated that the equilibrium isostatic depression in the northern Irish Sea Basin may have been 400 to 500 m during the maximum glaciation. However, crustal rebound following deglaciation of glacio-isostatically depressed basins is known to be very rapid, as much as nearly 50 m within one thousand years in the early deglaciation (Andrews et al., 1973). Along the Cumbrian coast, therefore, there has been no more than 18 m of isostatic recovery during the last 13,000 years (Andrews et al., 1973). It was recorded that, at the height of the Devensian Glaciation, the Lake District ice was at least 760 m (2500 ft) in thickness, which covered all but the highest mountain tops and extended outwards on to the surrounding plains (Pennington, 1970). It therefore seems that, in terms of the equilibrium isostatic depression and rebound, the effect of the Lake District ice would be much less than that of the northern Irish Sea ice. But, in a local term, the effect of the Lake District ice could still be significant (see discussion in Chapter V).

Subsequent to the peak of the Devensian Glaciation around 18,000 yr. B.P., the Irish Sea Glacier retreated rapidly because of high relative sea-level (Eyles and McCabe, 1989). By before 14,500 yr. B.P., ice had disappeared from areas as far north as the head of Windermere (Pennington, 1978), i.e. 1500-2000 years earlier than the ice disappearance in southwest Scotland (Sutherland, 1984). During deglaciation, a few episodes of glacial readvance occurred as characterised in the north part of the Morecambe Bay area (Gresswell, 1951; Huddart et al., 1977), which left areas of glacio-fluvial deposits in the valleys and lowlands of the areas.

Thomas (1985a) represented that, conventionally, it has been assumed that the retreat was terrestrial and that the retreating ice margin was not in contact with the eustatically lowered sea level. During deglaciation in Morecambe Bay, varved sediments bear witness to post-glacial lake sedimentation (Knight, 1977). The varved clays, which are up to 16 m thick in the Bay, are overlaid by some 2 to 47 m of clays, silts and sands that Knight (1977) interpreted as deposition in an alluvial fan. A slight overconsolidation of these sediments was explained by desiccation. Vincent and Lee (1981) have reinterpreted the sedimentation of clays, silts and sands overlying post-glacial lake sediments as a large complex sandur supplied from wasting ice sheets to the north and the west. The results indicate that during a period of desiccation, this sandur provided the sediments interpreted as loess on all the limestone outcrops around Morecambe Bay, and mapped as loess by Catt (1977).

The chronology for these changes has not been established, but at least by around 15,000 yr. B.P. the Windermere Basin was ice free (Pennington, 1975a, 1978) and chloride-containing silts were being discharged from Windermere into Morecambe Bay (Holmes, 1968). It was also indicated (Tooley, 1987b) that the organic sedimentation in kettleholes elsewhere near Morecambe Bay does not appear to have started until about 12,000 yr. B.P. In Windermere, Pennington (1978) identified three main lithologic units: the Lower Laminated Clay, Interstadial Sediments and the Upper Laminated Clay, which marks the end of glaciation in north-west England. On the other hand, the climatic conditions during the Late glaciation in north-west England were demonstrated, and a detailed series of climatic periods of the Late glaciation were established (Pennington, 1977; Musk, 1985), based on results of pollen analyses (Lamb, 1977) and radiocarbon dating (Goudie, 1977). This sequence is: Oldest Dryas (pre-Bolling) to 12,750 yr. B.P.; Bolling from 12,750 to 12,350 yr. B.P.; Younger Dryas from 12,350 to 12,150 yr. B.P.; Allerod/ Windermere from 12,150 to 11,350 yr. B.P.; Youngest Dryas from 11,350 to 10,250 yr. B.P. However, Tooley (1987b, p32) indicated that "there is no evidence of the effects of these changing environmental conditions on sedimentation in Morecambe Bay, although the evidence may have existed in the cores, taken for the Morecambe Bay Feasibility Study (see Tooley, 1974; Knight, 1977)." The oldest dated record of environmental changes within Morecambe Bay occurs during the first millennium of the Flandrian Age (Tooley, 1978a; 1987b).

4.1.3. Flandrian deposits and landforms

As early as the beginning of this century, evidence dealing with Flandrian deposition in and around Morecambe Bay was recorded. Kendall (1900) described a buried peat in Barrow Harbour with altitudes ranging from -14.9 to -17.9 m O.D., and Reade (1902) recorded a buried peat in Heysham Harbour from -8.2 to -17.6 m O.D. These altitudes have been confirmed by more recent work in the Bay (Huddart et al., 1977; Tooley, 1974, 1978a, 1987b).

Tooley (1987b, p36) summarized that "marine sedimentation ended around Morecambe Bay at about the time of the decline of elm pollen, and this is strongly marked in this area: the change from estuarine clays and silts to Phragmites turfa and succeeded by woody detritus occurred at about 5000 B.P. at altitudes of 3.8 to 4.9 m O.D." He (1987b, p36) further indicated that "Although this is a small sample, it indicates a fundamental change in shape of Morecambe Bay at about the time of the 'elm decline', when extensive areas of former tidal flat would have been colonised successively by Phragmites, Scirpus and Juncus, and then by alder/oak fen." The extensive contraction in the size of the Bay was the consequence either of a fall of sea level or massive input of sediment or a combination of both factors. Arguments for a fall in sea-level include the widespread occurrence of the marine regression and independent evidence of a climatic deterioration (see discussion in Tooley 1978a). In fact, many pollen diagrams from sites around the Bay (Oldfield, 1960a, 1960b, 1963, 1965; Oldfield and Statham, 1963, 1965; Smith, 1958, 1959; Gresswell, 1958; Dickinson, 1973; Barnes, 1975) show marked elm declines and 'Landnam' or 'Land-taking' phases. These may indicate extensive forest clearance by prehistoric folk (Garbett, 1981) or by climatic factor (Pennington, 1975b) or the combination (Smith, 1981) in early neolithic times. Around the north-east margins of Morecambe Bay, the elm decline has been placed within the range from 5435 to 4810 B.P. (Tooley, 1987b). The effects of extensive clearances over a 600 year period would be soil erosion and an increased sediment supply to the Bay (Tooley, 1987b).

Evidence of elm decline was also dated to 4990±140 B.P. (Gak 2293)(Hicks, 1971) at Totley Moss in the south Pennines and 5220±120 B.P. (Gak 2915) (Turner et al., 1973) at Weelhead Moss in the north Pennines. Hirons and Edwards (1986, p131) indicated that "Seventeen radiocarbon dates provide chronologies for the sites (in northern Ireland) and date the elm decline to between 5050 and 5375 B.P., the subsequent start of increased elm pollen percentages to between 5010 and 4850 B.P., and the beginning of a second decline in elm pollen to between 4330 and 4260 B.P." Wimble (1986) recorded evidence of the second elm decline at Foulshaw Moss, beginning in 3870±70 B.P. (CAR 544) and ended in 3690±70 B.P. (CAR 554) and 3590±70 B.P. (CAR 543).

Tooley (1987b, p36) stated that "in addition to the marine regression of 'elm-decline' age, there are a few dates recording more recent transgressions at different altitudes. For example, at Arnside Moss a saltmarsh soil overlies woody detrital peat at an altitude of +5.7 m O.D. and this has been dated to 1545±35 B.P. (Hv. 3461); further south, at Heysham Moss, a grey-blue, clayey silt is overlaid by peat dated to 4190±150 B.P. (Hv. 2920)," and "the most complete sequence of post-elm decline marine transgressions has been recorded from the catchment of the Skelwith Pool, south of White Moss, where 4 periods of transgressive and regressive overlaps are registered between +2.7 and +5.9 m O.D."

The Flandrian history of Morecambe Bay was characterised by periods of organic deposition when extensive saltmarshes, reedswamps and fens were more characteristic than at present. One of the most characteristic lowland landform was the 'estuarine moor' or raised bogs of the Morecambe Bay coast (Shimwell, 1985). They contain a record of the climatic history of the area and of the impact of man on the surrounding vegetation (Oldfield, 1963), and also prehistoric artifacts and bog burials (Tooley, 1987b).

Smith (1959) described 'retardation layers' in the stratigraphy of the raised mosses or moors adjacent to the Kent estuary --- Nichols Moss and Foulshaw Moss, and in the Gilpin Valley --- Helsington Moss. At the latter site, an upper retardation layer has been dated to 1514±100 B.P. (Q. 83; Godwin and Willis, 1960). Dickinson (1973, 1975) described the raised bog complex near Rusland and identified and dated three recurrence surfaces, indicative of cool and wet periods. Wimble (1986) also investigated three sites on the north shore of Morecambe Bay, and described and dated a number of recurrence surfaces and retardation layers. On the southern shore of Morecambe Bay, Oldfield and Statham (1965) described the raised mosses known as Pilling and Cockerham Mosses, and recorded fossil remains of Scheuchzeria palustris indicative of rapidly deteriorating conditions. Barnes (1975) indicated a few recurrence surfaces St. Rawcliffe Moss. Godwin and Willis (1960) described and dated a trackway west of Rawcliffe Moss to 2760±120 B.P.

4.2. Previous Investigations of Flandrian Stratigraphy

During the last two decades, detailed investigations dealing with histories of vegetation, stratigraphy of coastal deposition and sea-level changes have been carried out (Fig. 4.1.). Of these the most significant are the stratigraphic and pollen analysis by Dickinson (1973) in Rusland Valley; Oldfield and Statham (1963, 1965) in Ellerside Moss and Cockerham - Pilling Mosses; Smith (1959) in Foulshaw Moss and Helsington Moss; Oldfield (1960a,b, 1963) in Silverdale Moss; Barnes (1975) in Pilling Moss; and Tooley (1974, 1978a, 1987b) and Huddart et al. (1977) in Heysham Harbour and in the Bay. From these works, a summary can be made of the Flandrian history of Morecambe Bay. The estuaries feeding the Bay are characterized by periods of marine inundation which left clastic deposition, and periods of marked expansion of extensive saltmarshes, reedswamps and fens which were more characteristic than at present (Tooley, 1987b). What follows this section will review the previous investigation of the Flandrian stratigraphy in and around Morecambe Bay, which will be compared with the present survey for stratigraphy in Skelwith Pool.

4.2.1. Morecambe Bay

During the Morecambe Bay Barrage Feasibility Survey, beds of peat were encountered in some of the boreholes at altitudes ranging from -11.13 to -16.40 m O.D. (Fig. 4.2.). The peat, which in every case was a hard, consolidated, dry, and laminated deposit, was overlain by clay, silts and sands which from their included micro- and macro-fossil assemblage were demonstrably marine in origin (Tooley, 1974, 1978a, 1987b). Knight (1977) described the general stratigraphy of the unconsolidated sediments on

Morecambe Bay as:

Stratum	Range of top level (m O.D.)	Range of thickness (m)
1. upper sand	+4 to -2	3-15
2. sand, silt and clay	-2 to -9	1-12
3. lower sand	-6 to -18	0-16
4. clay, silt and sand	-1 to -30	2-47
5. varved clay	-17 to -49	0-16
6. boulder clay	-9 to -46	1-55
7. bedrock		

The peat beds lie between Layers 4 and 5. The varved clay and boulder clay are deposits of the late Devensian and deglaciation. Tooley (1974, p24-25) described that "micro- and macro-fossil analysis of the biogenic (the peat) sediment permitted an estimate to be made of the relationship of the sediment to a former position of sea level." On this basis, of the five radiocarbon assays from Morecambe Bay, all are corroborated by the local pollen assemblage zones from the sampling sites, but only the samples from boreholes A5, B1 and C6 (see Fig. 4.1. for their locations) contain evidence of rising freshwater tables, indicated by rising frequencies of aquatic taxa, replaced by saltmarsh communities. He (1974) also indicated that the age of the peat sediments were dated to between 8740±65 B.P. (Hv. 3361) and 7995±80 B.P. (Hv.3362).

4.2.2. Areas around Morecambe Bay

The Leven Estuary

Previous stratigraphic investigations in the Estuary and the Rusland valley have been carried out first by Pearsall (1918), and later by Gresswell (1958), Oldfield and Statham (1963), Dickinson (1973), Huddart et al. (1977) and Tooley (1987b) (Fig. 4.3.).

Rusland valley is in the southern part of the Lake District and drains towards Morecambe Bay. From Rusland to the head of the estuary at Greenodd, a distance of 5 miles, the valley floor is a flat expanse, never higher than 6 m above mean sea level. The Rusland bogs occupy an inter-mediate position between the lakes of the Lake District and the Mosses of the Estuary area.

Pearsall (1918, p56) described the stratigraphy in the Rusland Moss as "underneath the surface Sphagnum peat, at varying depth, between 1.5 and 3 m, there is a layer of dark brown peat, ... This layer overlies a wood layer of about 20-30 cm in thickness, chiefly composed of Betula, with hardly recognisable, abundant remains of Salix and Alder below. The wood, often upright and rooted, has occasionally been cut. ......Clayey peat, often humus stained to 3.1 m, is found immediately below, containing Phragmites, Typha, ... The basement clay is identical with that of Esthwaite (lacustrine facies)."

Afterwards, a number of borings were put down across the Rusland Moss (Fig. 4.3.) by Dickinson (1973). Based on pollen analysis, she indicated

(1973, p884) that "the clay in 650-673 cm in boring R.VII is not marine in origin, ... and the clay is definitely fresh-water with no trace of Foraminifera or halophytes, and the very high ratios of Corylus pollen and small amounts of Ulmus and Quercus indicate that the clay was deposited earlier than the main Boreal/Atlantic marine transgression." However, "Signs of rapidly rising water levels are seen, especially in boring R.VII (510-650 cm) where successive peaks in the pollen diagram indicate that Filipendula gives place to Sparganium, which is succeeded by Cyperaceae." She also pointed out (1973, p884) that "the level R.VII-540 cm is significant in arriving at some estimate of the actual lake level and the depth of water. Below 540 cm the peat is fine and detrital. At 540 cm, it becomes very humified and the pollen is much more concentrated. Above 540 cm, the peat is coarser and contains some whole rhizomes; the pollen, too, is sparser. These changes in peat texture and pollen concentration suggest a change from open water to reed swamp, when Phragmites was able to grow in situ, and peat accumulated more rapidly." The 540 cm level was determined to be around 6000 B.P. by pollen analysis and would indicate a water level standing at 4.5 m above present (mean) sea level (Dickinson, 1973), which corresponds very closely to the level of the top of the marine clay around Morecambe Bay (Gresswell, 1958; Tooley, 1987b). Dickinson (1973) further indicated that there was a period of rapid accumulation of Phragmites peat averaging over 1 m per thousand years (during 6000-5000 B.P.).

To find the limit of marine clay, Dickinson (1973) put borings down the valley further south around the present tidal limit (Fig. 4.3.), and discovered that the marine clay was deposited only as far up as the narrow part of the valley just below Crooks Bridge (SD 344 864). From the boring R.XXXVI (Fig. 4.4.), she indicated (1973, p883) that "much of the rise in sea-level is represented by peat deposits, and the alternation of Phragmites and wood peats indicates an irregular rise in sea-level," and "the clay sampled at R.XXXVI-510 and 530 cm is of marine origin since it contains Foraminifera of Globigerina type and also sponge spicules and fragments of Radiolaria. These are also found in the clay in R.XXXVII, which was sampled at 335, 375, 425 and 520 cm" (Fig. 4.4.). She finally reported (1973, p883) that "Pollen analysis at R.XXXVII-530 and 320 cm, near the base and top of the marine clay, shows high percentages of Pinus, Quercus and Betula ...... This indicates the clay was deposited at this site during the period Flandrian Id." The boring records of R.XXXVI and R.XXXVII (Dickinson, 1973) (Fig. 4.4.) show that a thin peat layer of about 10 cm in thickness is sandwiched by marine clay layers, and lies at altitudes of from -0.1 to -0.7 m O.D. In 1979, in the same site about 300 m south to the Crooks Bridge (SD 3441 8627), Tooley sampled the thin peat and dated it to 7750$\pm$100 B.P. (Har.3709) (Tooley, 1987b) (Fig. 4.4), which confirms Dickinson's result that the estuarine clay was deposited in this site during period Flandrian Id.

In Ireland Moss near the Pool Bridge (Fig. 4.3.), just about 2 km south of the Crooks Bridge, Gresswell (1958) put a number of borings down on the north-west side of the river. From the pollen analysis of one of the borings (LP12, Fig. 4.4.), he pointed out that the period of transgression was centred on the transition between pollen zones VI and VIIa, the Boreal-Atlantic transition.

Further south, in Roudsea Wood, Birks (1982) illustrated a pollen and stratigraphic record from a small hollow (SD 333 822; RSW, Fig. 4.4.) situated between the two parallel Carboniferous ridges of Roudsea Wood National Nature Reserve, where a shallow alluvial valley drains northward into the River Leven. He reported (1982, p348) that "the silty clay (underneath the peat accumulation) contains marine dinoflagellate cysts, sponge spicules and Radiolaria Fragments", and "the sea presumably flowed through the valley between the ridges of the wood today and deposited estuarine silty clays". For a basal date for the organic sediments at the site, he suggested that the marine transgression occurred before 6680 B.P. The contact between the clay and the peat was levelled to $+2.29\pm0.1$ m O.D. during the present study.

At Ellerside Moss (Fig. 4.3.), Oldfield and Statham (1963) put a boring down in the crown of the bog (SD 335 480; EM, Fig. 4.4.). Based on pollen analysis for this borehole, they indicated that the transition from reed-swamp peat to Eriophorum peat suggests a falling in sea level that occurred during the time between FII and FIII, marked by the main decline in elm pollen. They (1963, p62) also reported that "in the lowest sample, the peak in Alnus and

Filicales frequencies suggests that alder carr probably existed not far away, perhaps on the marine clay surface. ...... The Chenopodiaceae peak in the same sample suggests that salt marshes too were close to land." The marine transgression ended at an altitude of +3.72 m O.D. in this site, shortly before 5435±105 B.P. (Hv.3844) which is the date on the reed-swamp (Phragmites) peat immediately above the marine clay (Huddart et al, 1977, Tooley, 1987b).

In the lower valley of the Leven Estuary, Tooley (1974, 1987b) constructed a transect of boreholes (Fig. 4.1. and 4.5.) which shows that a layer of till sediments immediately overlies on the bedrock, succeeded by limnic clay. This clay is overlaid by a thin layer of peat deposits dated to between 7995±80 B.P. (Hv. 3362) and 8740±65 B.P. (Hv. 3361) at altitudes between -16.5 and -11.1 m O.D. Above the peat deposits, there is a thick layer of marine clays and silts up to the surface. The date of 7725±95 B.P. (Hv.3360) from borehole C7 (Fig. 4.5.) is probably much younger than it should be (Tooley, 1987b).

In summary, the Flandrian transgression started to affect deposition in the Leven Estuary after 7995-8740 B.P. and ended at least until or later than the time of the main decline of elm pollen. As a result of the rising sea-level during the eighth millennium and the fluctuations of sea level since then, alternate organic and minerogenic deposits were laid down along the Leven Valley and Estuary. In which, four organic strata can be significantly identified. The first (basal) peat layer is dated to 8740-7995 B.P. at altitudes ranging from -16.5 to -11.1 m O.D. The second (thin) and third peat layers are dated to 7750 B.P. at around -0.3 m O.D. and 6680 B.P. at around 1.5-2.0 m O.D. While the fourth (top) peat is dated to 5435 B.P. (the beginning of the main elm decline) at altitudes roughly ranging from 3.5 to 4.0 m O.D.

The Kent Estuary

In Helton Tarn within the Winster valley (Fig. 4.1.), Smith (1958) has put down a series of borings, and made detailed investigations on stratigraphy and pollen analysis. The stratigraphical and pollen analytical evidence suggests that at the maximum of the early Post-glacial marine transgression, the sea overflowed a rock bar that is now at about 5 m O.D. into the Helton Tarn basin and laid down a layer of clay during the earliest part of Atlantic time. The stratigraphy indicates that a layer of blue-grey silty clay is overlaid by a layer of coarse detritus mud (named as the third clay layer) which at the margins of the basin contains some organic detritus. This coarse detritus mud was presumed to be laid down by an incursion of the sea into the freshwater lake during early Atlantic time. This explanation is preferred (Smith, 1958) for the following reasons: (1) the reduction of the percentages of pollen of Alnus and Betula which were presumably the local trees of the low-lying areas, and the increase of the percentages of pollen of Quercus and Pinus which presumably were growing on higher and drier ground, is typical of marine transgression elsewhere e.g. in the Fenland (Godwin, 1940; Shennan, 1980, 1986a); (2) pollen of Chenopodiaceae is continuously present throughout the third clay layer; (3) the estuarine clay to the south of the rock bar across the Winster Valley below Helton Tarn rises to a height of +4.7 m O.D. and as far as can be determined the height of the rock bar, where it is traversed by the river, was originally +5.0 m O.D.; (4) the mires (or mosses or moors) to the south of Helton Tarn, which lie on the estuarine clay, had begun to form early in zone VIIa. This date is within the limits of chronology of the date for the end of the third clay layer at Helton Tarn, based on pollen analysis.

One year later, Smith (1959) investigated the stratigraphy of three sites on Foulshaw Moss, Helsington Moss and Nichols Moss, and indicated that the stratigraphy at the three sites is generally quite similar. He (1959, p109) described that, "A few reeds are present at the top of the estuarine clay at each site, and the lowest organic deposit, which lies on the estuarine clay, is a reedswamp mud or reedswamp peat. ......Above the reedswamp deposits, there is a considerable thickness of Sphagnum peat containing occasional remains of Eriophorum and Calluna." The marine transgression represented by the estuarine clay came to an end early in zone VIIa of Godwin's pollen zone scheme. The surface of the estuarine clay is seen from the stratigraphic diagrams to lie between +3.8 and +4.7 m O.D. The end of marine conditions was dated later by Godwin and Willis (1961) to from 5277±120 B.P. (Q.85) in Helsington Moss to 4616±112 B.P. (Q.88) in Foulshaw Moss.

Also in Helsington Moss, Gresswell (1958) suggested that the deposits of marine transgression ended at an altitude of +4.36 m O.D. It is comparable to Smith's measurements.

On the south shore of the Kent Estuary (Fig.4.1.), Oldfield (1960a) demonstrated the late Quaternary changes in climate, vegetation and sea-level in Lowland Lonsdale, and recorded transects of borings for examination of Post-glacial stratigraphy of the Siverdale Moss. He (1960a) reported that in Siverdale Moss there is a layer of marine clay sandwiched by organic deposits. The basal terrestrial sandy clay is succeeded by a dark brown friable oxidized deposit. This then is succeeded by a layer of detritus greasy blue-grey clay-silt which comprises mostly <u>Equisetum</u> and <u>Phragmites</u>. This marine clay-silt is succeeded by a <u>Phragmites</u> layer which passes up into an oxidized deposit rich in <u>Alnus</u> remains. From the pollen content of the organic deposits, both boundaries above and below the marine clay-silt can be dated to the early FII, and the upper peat has been radiocarbon dated (Oldfield, 1960a) to 6590±144 B.P. (Q. 260, at +3.55 m O.D.) and 5865±115 B.P.(Q. 261, at +3.85 m O.D.). The radiocarbon date of the lower peat, 5734±129 B.P. (Q. 256, at +2.80 m O.D.), must be too young, and should be dated to about 7000 B.P. (Oldfield, 1960a).

At Arnside Moss (Fig. 4.1.), a free-face pit (SD 4672 7895) was investigated and sampled for pollen analysis and radiocarbon dating, by D. Kerr in September 1966 (Tooley, per. comm.). The profile recorded shows that a peat bed from 0.67 to 1.44 m in depth is underlaid by marine clay and overlaid by sandy peat and inorganic sands. The lowest part of the peat bed is dominated by Phragmites with clay, a sample taken from 1.38 to 1.42 m with an altitude of 4.98±0.02 m O.D. was dated by pollen analysis to late FII and by radiocarbon assay to 5015±100 B.P. (Hv.3460) (Huddart et al., 1977; Tooley, 1982, 1987b). The uppermost part of the peat bed is composed of amorphous peat dominated by a pollen assemblage indicating a fen community. A sample is taken from 0.71 to 0.74 m at an altitude of 5.56±0.02 m O.D., and dated to late FIII and to 1545±35 B.P. (Hv.3461) (Tooley, 1982, 1987b). This radiocarbon date could be a bit younger than the real age of the deposit because the sample is too close to the ground surface and is possibly penetrated by young carbon. Tooley (1987b, p36) summarised that "at Arnside Moss in Lowland Lonsdale, shortly before 5015±100 B.P. (Hv. 3460), marine conditions ended at an altitude of +4.98 m O.D.; and a saltmarsh soil overlies woody detrital peat at an altitude of +5.78 m O.D. and this is dated to 1545±35 B.P. (Hv. 3461)."

In summary, the stratigraphy suggested by the previous work in the Kent Estuary comprises two periods of marine clastic deposits which are separated at +2.80 to +3.55 m O.D. by a layer of peat dated to around 6590 B.P. The marine transgression ended during the periods from 5277 to 4616 B.P. at altitudes from +4.88 to +5.18 m O.D. It must be noted that these two levels are about 1 m higher than their counterparts in the Leven estuary.

The east-south coasts

In the Hawes Water Basin which drains through the Leighton Moss into

Morecambe Bay (Fig. 4.1.), Oldfield (1960a) described that at the lowest part of transect C which runs along the edge of the present Phragmites marsh, is increasingly sandy and silty towards its base, which is succeeded upwards by a mixture of sand, silt and gravel in a smooth dark grey clay matrix. These are succeeded by cream calcareous muds; the succeeding deposit is a mixture of this calcareous mud with clay, silt, sand and large pebbles. Above this a narrow band of olive-green fine detritus mud succeeds, followed by a peat with Phragmites remains and finally, by an oxidized deposit. Oldfield (1960a) also indicated that in the part of the basin nearest to the lowest point on the rock-bar (5.0 m O.D.) to the seaward, the Phragmites peat in boring V has developed on a greasy blue-grey silty clay which is related to a marine transgression. The pollen analysis suggested that the marine silty clay was deposited during FII, and the Phragmites peat, in FIII.

Further south, at Heysham Moss, it is reported (Huddart et al., 1977; Tooley, 1987b) that a grey-blue clayey silt is overlaid by peat which is dated to 4190±150 B.P. (Hv. 2920) at an altitude of +4.49 m O.D.

In Heysham Harbour, a buried peat, overlaid by marine clay, from -8.2 to -17.6 m O.D. was reported by Reade (1902). Shotton and Williams (see Tooley 1974, 1978a) dated this peat to 9270±200 B.P (Birm. 141) at -17.6 m O.D., 9195±155 B.P. (Birm. 139) at -16.3 m O.D. and 8925±200 B.P. (Birm. 140) at -16.0 m O.D.

About 2 km off shore from Morecambe (Fig. 4.1.), a peat was found in the boring C6 (Tooley, 1978a) at altitudes of from -15.73 to -16.95 m O.D., and dated to 8330±125 B.P. (Hv.3462). Pollen analysis (Tooley, 1978a) indicated that fen community dominates the peat but with reedswamp pollen grains at the top and bottom.

Between the Wyre and the Lune, most of the surface of the coastal area comprises reclaimed raised bog and saltmarsh. Oldfield and Statham (1965, p71-72) indicated that "at Head Dyke Lane Phragmites rich clay-mud intervenes between the basal marine clay-silt and the overlying peat," and that "no peat accumulation took place at either Cockerham or Head Dyke until some time after the Elm Decline, in Zone VIIb or later." Then they (1965, p76) summarised that "the Cockerham and Pilling Mosses lie on a plain of marine alluvium related to the mid-postglacial culmination of sea-level in the area. ...... and no peat accumulation took place at Cockerham and Pilling until about 1400 B.C. or later. The lower part of each peat profile records carr woodland which was succeeded by bog at an horizon marked by a Bronze Age trackway, Kate's Pad (Godwin and Willis, 1960) and radiocarbon dated to 2760±120 B.P., Q.68)."

In the same area, Barnes (1975) has carried out a series of detailed stratigraphic investigation and pollen analyses. He indicated that there are three flooding horizons of sea water found in the area. He further suggested that the third flooding horizon is associated with the laying of the prehistoric trackway (Kate's Pad), timbers from which provided a radiocarbon date of

2760$\pm$120 B.P. (Godwin and Willis 1960, Q.68). The second flooding horizon is frequently recorded, ... Material sampled from immediately above the flooding surface at 130 cm at Lousanna 2B was radiocarbon dated to 3370$\pm$120 B.P. The first flooding horizon was only locally distinguished at Lousanna 1, 2B, and 2A. It lies at 205 cm at Lousanna 2B above the FII/FIII boundary which is dated to around 4900$\pm$450 B.P. (Hv. 3052) in the area.

Synthesis

It is quite clear that the Flandrian alluvial and lacustrine deposition in the central part of the 'Bay' was continued until the early 8th millennium. During the same time, there were extensive peat deposition along the east and west margins of the 'Plain' or 'Lake'. Around the beginning of the 8th millennium, sea water started inundating the area now called Morecambe Bay. By about the early 7th millennium, not only the central part of the Bay, but also the four major estuaries, were entirely inundated by sea water and dominated by marine clastic deposition. During the period between the 7th millennium and the 4th millennium, alternate organic and clastic sediments were deposited within the estuaries and some small embayments around the Bay because of the fluctuating sea level. Since the 4th millennium, organic deposition was dominant within the estuaries and the marginal embayments as these have been silted up.

The previous stratigraphic investigations have provided general information of Flandrian sea-level history. But it is indicated that the stratigraphic data for the period between the 7th millennium and the 5th millennium and the period since the 4th millennium are not sufficient in detail. The present study was therefore carried out in order to fill these two time gaps.

4.3. Stratigraphic Survey in Skelwith Pool

Skelwith Pool (SD 3481) area lies on the east shore of the Leven Estuary, in the north part of Morecambe Bay (Fig. 4.6.). The low-lying area is about two kilometres in width and ranges between 5.5 m and 8.5 m in altitude. Skelwith Pool is or used to be a tidal creek which runs from the solid in the east, cuts through the mosses with its zigzag course, meets a small stream from the south and finally feeds into the estuary in the west through the solid rocks (Fig. 4.6.). However, the area of Skelwith Pool comprises Stribers Moss, Deanholme Moss (also named as White Moss) and the cultivated farmland flanking on the creek. This area merges in the north to the Deer Dike Moss, beyond which is the Fish House Moss. To the south, it is bounded by the Ellerside Moss (Fig. 4.3.).

Skelwith Pool, as it named, is well sheltered by its basin background. Silurian rocks rise over 100 m with a N-S trend along the landward margin. Carboniferous rocks are scattered on, as isolated hills with altitudes varying from 10 to 30 m, along the east shoreline of the Leven Estuary. For instance, Roudsea Wood, one of the hills and the Natural Reserve, lies north and west to Skelwith Pool (Fig. 4.6.). During the Flandrian, Skelwith Pool would have been sheltered, ensuring a low energy marine or marine-brackish environment with probably gradual sedimentation, little marine erosion and little fluvial influence. The Flandrian deposits found in the area of Skelwith Pool exceed 12 metres in thickness (referring to the Bore 2).

The central part of the area flanking the creek has been cultivated and drained to be pastures since the 1850s (data from local drainage book, Holke Estates Office). The Deanholme Moss and Stribers Moss have been drained since the end of the 1970s, while the landward part of the raised bog still retains its shrub and Pine plantation.

4.3.1. Stratigraphic survey

A good arrangement of boreholes to investigate a site which has not been surveyed is very important, especially when the work needs to be finished in a limited length of time.

In the present study, the stratigraphic survey was carried in three stages. In the first stage, three boreholes (Bores 11, 4 and 12) were put down in the central part of Skelwith Pool and Deanholme Moss (Fig. 4.6.) for a primary survey of the stratigraphy in the site. The result of this survey has established that the Flandrian strata in Skelwith Pool are composed of many sequences of clastic and organic deposition, which means that much information of changes in coastal environment and sea level had been preserved at the site in Skelwith Pool. In the second stage, ten boreholes (Bores 0, 1, 2, 3, 5, 6, 7, 8, 9 and 10) were sunk along an approximately straight line extending from Bore 4 to both landward and seaward directions in an interval of 200 m, in order to reveal the general stratigraphy of the site. Meanwhile, two pits (PIT1 and PIT2) were dug near Bore 4 for a detailed investigation and sampling. The result of the second survey indicated that most evidence of changes in sea level and coastal environment remained centralized in the area between Bores 12 and 6. This suggests that the next stage of survey should be arranged and concentrated in this area of Skelwith Pool. Therefore, six boreholes (Bores 13, 14, 15, 16, 17 and 18) were then put down between Bores 12 and 6 at intervals of from 20 m to 50 m. Meanwhile, in order to get samples for laboratory analysis, PC-1, a Piston Core was sunk at the same point as Bore 5 where five sequences of organic deposits were obtained. Employing a Russian-type sampler, Bore PIT2C was also put down in the same point where PIT2 was dug, in order to obtain the deeper samples. Based on these surveys, a stratigraphic transect from landwards to seawards across Skelwith Pool was established (Fig. 4.7.).

4.3.2. The borehole records

In Skelwith Pool, twenty boreholes were put down and two pits were dug approximately along an east-west line from landwards to seawards. Records or these boreholes and pits are listed in Appendix I. Three of them, PC-1, PIT2 and PIT1, were sampled in detail for analysis of the physical components, diatom and pollen content, and radiocarbon assay.

PC-1 was obtained from the cultivated pasture immediately east of Skelwith Pool. The point where a Piston Corer was sunk was 12 m away from the creek (Fig. 4.6.). Sediment samples of 530 cm in depth and 5 cm in diameter were obtained. This bore includes all significant organic layers from this site, except the upper peat which is described from PIT1 (Fig. 4.8.).

The stratigraphy of PC-1 (Fig. 8.) shows that the sediment at the bottom of the core is composed of stiff silt of a pinky grey colour (Stratum 1), which becomes clayey with occasional Phragmites fragments (Stratum 2). These clastic deposits are overlaid by fine organic materials with leaves (Stratum 3), which is succeeded upward by silty clay (Stratum 4). According to the pollen analyses, Stratum 3 might be interpreted as gyttja . Above Stratum 4, the sediments change to be clayey with fragments of Phragmites, then humified Phragmites turfa and detritus (Stratum 6) which change gradually to be of clay with organic substance. Further upwards, the clastic sequences become coarser from silty clay (Stratum 8) to silt and sand (Stratum 11). The sand, through a transition of grey clay with Phragmites detritus, is overlaid by a layer of organic substance with Phragmites turfa and detritus (Stratum 13) which is succeeded by silty clay (Stratum 14). The clay is overlaid by Phragmites detritus (Stratum 15), then silt and clay again which is succeeded by a partly-humified humus substance with herbaceous rootlets (Stratum 17), then clayey silt at the top. In summary, five sequences of organic deposition intercalating into clastic sediments are identified from PC-1, which are considered to be significantly related to the history of Flandrian sea-level changes and the changes in coastal environment.

PIT2 was dug on the north side of an artificial ditch, about 220 m east of PC-1. The pit was 1.5 m deep, and two monolith samples of 10 x 10 x 50 cm^3 and one of 10 x 10 x 25 cm^3 each were collected. The stratigraphic record of PIT2 is listed in Appendix I, and the diagram is showed in Figure 4.8.

The sedimentary sequences from PIT2 suggest that a layer of Phragmites turfa (Strata 2-6) is sandwiched by silty clay (Stratum 1) and sandy and silty clay (Stratum 7). Within the peat bed, the sequences from depths of 86-90 cm, 100-104 cm, and 112-120 cm are composed of about 15 percent clay. Further upwards, the top peat of Phragmites turfa is found, overlaying the upper clastic sequence (31-86 cm). In order to ascertain the origin of the clastic component (15 percent clay) from 100-104 cm, samples from this layer were examined for diatoms, and the results are discussed in the following section, Section 4.4.

At the same site of PIT2, a Russian-type sampler was employed to collect the deeper samples. This is named as PIT2C. From the PIT2C (Fig. 4.8.), a layer of organic deposits is found at a depth of 202-212 cm, which is sandwiched by clastic sequences. The upper part of the organic layer (202-205 cm) comprises partly-humified Phragmites fragments, whilst the lower part (205-212 cm) is composed of clayey organic substances with a few fragments of Phragmites.

PIT1 was dug on uncultivated mossland where drainage had been attempted in 1979/80. It was 39 m towards the western margin of the Deanholme Moss, where the surface rises up to around 7.5 m O.D. It was 20 m north to PIT2. The pit was 2.5 m deep, and five monolith samples 10 x 10 x 50 cm^3 and one 10 x 10 x 25 cm^3 were taken for laboratory analysis. The aim was to investigate the sequences of the top thick peat deposition in this small area. The sedimentary sequences downward from the bottom of the pit have been examined by Bore 4, using a gouge sampler. The stratigraphic record of the pit is shown in Fig. 4.8.

The excavated face of the pit suggests that: above the contact between the peat and the clastic sediments below, Stratum 1 is a layer of Phragmites turfa, which becomes silty and clayey upward into Stratum 2, where there are more silty clay in the seaward side of the pit. Further upwards, there is a thick layer of pure Phragmites turfa (Stratum 3), overlaid by Phragmites turfa with many more birch branches and roots (Stratum 4), followed by a mixture of Phragmites and Sphagnum turfa (Stratum 5). Above it, Sphagnum turfa dominates in the 4 remaining strata. However in Stratum 6 there are some Phragmites fragments, a few clastic materials (wind blown sands ?) in Stratum 7, and more herbaceous rootlets in Stratum 8 and Stratum 9.

4.3.3. The transect of boreholes

Employing software packages of the STRAT5 and the GHOST80, borehole records from Skelwith Pool have been plotted as a stratigraphic transect (Fig. 4.7.). The transect suggests that: (1) the changes in sedimentation type or facies are greater in the central part rather than the landward margin and the seaward side of the Skelwith Pool; (2) in the lower sequence, the organic layers at altitudes ranging around 0 and 2 m O.D. are dominated by Phragmites detritus or organic substances; (3) whilst in the upper sequence, above 3 m O.D., Phragmites turfa and detritus and subsequent fen peat dominate the landward side from PIT2. But, organic substances intercalated by clastic sediments are characteristic in the seaward side from Bore 14; (4) the highest level of deposits of Phragmites peat is found in PIT1 and Bore 4 at 5.614 m O.D. which is a bit higher than the present-day level of the local MHWST, about 4.9 m O.D. (referring to the tide gauge in Ulverston, see Fig. 7.1.).

It must be emphasised that correlation of the organic layers from different boreholes could be made only with consideration of the component of the sediments, altitude of the layers, evidence of pollen assemblages, radiocarbon dates if available, and the most important factor, the process of sedimentation. It is because even in such a small area, about 2 km^2 in area, that sediments at the same altitude might not have been deposited at the same time; and sediments deposited at the same time might not be of the same facies (components). However, the sedimentation under the same (transgressive or regressive) process could be more easily correlated and is more meaningful for reconstructing sea-level history. For instance, the contacts between the uppermost silty clay and the Phragmites of the top peat from Bore 18 to PIT2 rise in altitude from 3.86 to 4.51 m O.D. They might not be of the same age, but they probably represent a process of sea-level rise in a low rate, as well a seaward movement of the coastline. It can therefore be indicated that the combination of litho-stratigraphic, bio-stratigraphic and chrono-stratigraphic correlations is necessary and important for analyzing sedimentation and its relationship with the changes in sea level, which will be discussed in Section 4.7.

4.4. Diatom analysis

Samples collected from PIT2 pit and PC-1 core were prepared for analysis of diatoms. Five samples from the lower part of PIT1 were examined, but very few diatoms were found. Only a piece of Triceratium sp. and a Foraminifera were found in the clayey substance from Stratum 2 at 236-242 cm of PIT1. In addition, peat samples from boreholes C7, A5, C8, C6, B1, M1 and M2, as well as silty clay samples from boreholes M1, M3 and M5, were also examined during the present study. Results of these examinations are presented in the following sections.

4.4.1. Diatoms from PC-1

Sixteen samples from the clastic deposits of the PC-1 were prepared for diatom analysis. From these samples, diatoms of 113 species were identified, and over 200 individual valves were counted for most of levels (Appendix III.). The aim of the diatom analysis for this borehole is to confirm the marine origin of the clastic deposits.

The results of the diatom counting in species (Fig. 4.9.) show that the clastic sediments separated by organic deposits (except for the uppermost levels) contain dominant diatoms of marine, marine-brackish species (around 65 percent) with some brackish species (about 30 percent) and a few fresh species (5 percent), in which planktonic species in each level comprise the majority. It means that the site of Skelwith Pool, except for the periods of accumulation of organic deposits, used to be of an intertidal inlet or sheltered embayment under intertidal marine conditions. Tidal currents would have been a major agent for sediment transportation and deposition. The high percentages of planktonic marine species and the approximately 30 percent brackish species contained in the clastic deposits seem to suggest that (1) the salinities of the tidal water used to be very close to that of normal sea water. In addition, the consistent population of fresh water species suggests that Skelwith Pool has received some fresh water probably from the small stream, particularly since the uppermost organic layer formed.

The individual valves of diatoms were also counted for each level (Fig. 4.10.). The results of individual valves counted present a similar image as the species counting indicated. Marine and brackish diatoms are dominant, except for the top of the borehole in which obvious influence of fresh water appears. In these diatom groups, Coscinodiscus stellaris Roper (M), Diploneis chersonensis (Grun.) Cleve (M), Grammatophora oceanica (Ehr.) Grunow (MB), Melosira sulcata (Ehr.) Kutzing (MB), Navicula distans (W.Smith) A.Schmidt (M), Nitzschia granulata Grunow (BM) and N. navicularis (Breb.) Grunow (B), Rhaphoneis amphicera Ehrenberg (MB) and R. surirella (Ehr.) Grunow (MB), and Stauroneis amphioxys Gregory (BF) are the characteristic species.

Referring to the variation in percentages of each diatom group (e.g. Marine planktonic, marine benthonic, ...), it is likely that the planktonic marine and marine-brackish diatoms obviously increase from 510 cm to 459 cm, while the benthonic marine and fresh water diatoms decrease. Further upwards from 459 cm to 432 cm, however, marine and marine-brackish diatoms decrease while fresh and brackish diatoms increase. These changes in diatom groups coincide with the change in deposition from intertidal silty clay (Stratum 2) to fine organic material (Stratum 3). Above the organic layer from 418 cm to 405 cm and 330 cm, the planktonic marine and marine-brackish diatoms increase considerably while brackish and fresh water diatoms decrease. Similar changes from the dominant planktonic marine and marine-brackish diatoms or vice versa also occur at the upper and lower contacts of the uppermost organic layer (Stratum 17).

Tidal currents could have carried planktonic marine species of diatoms into Skelwith Pool, where these diatoms might have been subsequently deposited, during periods of higher relative sea-level. The alternating occurrence between dominant planktonic marine and marine-brackish diatoms and dominant fresh and brackish water diatoms may related to the fluctuation in sea level. The benthonic marine and brackish species of diatoms only live in a relatively stable condition of shallow water, e.g. subtidal area (Jin et al., 1982). The occurrence of benthonic marine and brackish diatoms of relatively higher percentage may be a sign of a sedimentary environment of lower intertidal or subtidal zone.

It can therefore be summarised that in terms of sedimentary environment changes at PC-1, the marine influence weakened from the bottom to the top of Stratum 2. After the deposition of Stratum 3, sea water in the site became deeper and the salinity of sea water was relatively high at the time Stratum 4 was deposited. This episode was followed by a period of weak marine influence when the organic clay and Phragmites (Stratum 5-7) were laid down at the site. Afterwards, sea water became deeper again when Strata 8-11 deposited, but became relatively fresher during deposition of the organic clay

(Stratum 12) and the fine organic material (Stratum 13). This sort of changes in sea-water depth and salinity happened again, allowing the silty clay (Strata 14, 16 and 18) and the intercalated organic sediments (Strata 15 and 17) to be deposited.

4.4.2. Diatoms from PIT2

Eleven samples were selected from PIT2 for diatom analysis. However, four of them at levels of 65, 50, 35 and 25 cm contain only a few diatoms of marine and brackish species. The other seven samples are selected from the lower peat bed, 85-124 cm in depth (Fig. 4.8.). The aim of examining these samples is to demonstrate the changes of diatom groups in the saltmarsh sequence, and to confirm the marine origin of the clastic components in 100-104 cm (PIT2, Fig. 4.8.). For this purpose, over 200 valves of diatoms are identified and counted for each level (Appendix III). The results of diatom counting represent a trend of changes in diatom groups (Fig. 4.11.). From the lower contact of the lower peat upwards, diatom groups change from dominant marine and marine-brackish species to brackish and brackish-fresh species, This coincides with the change from clastic deposition to organic deposition. Looking closer at the details of the change in diatom groups, it is suggested that the small peak of the (planktonic) marine species at around 100 cm coincides with the occurrence of clastic components (Fig. 4.7.), representing stronger marine influence. From 95 cm to 85 cm, coincided with the decline of brackish and brackish-fresh species, benthonic marine and brackish species increase, representing another period of marine influence.

Counting of diatom valves provide a similar result as that mentioned above (Fig. 4.12.). The results indicate that there are changes in specific species from Diploneis crabro Ehrenberg (MB) and D. chersonensis (Grun.) Cleve (M) in 124-117 cm, to Caloneis westii (W.Smith) Hendey (B), Navicula crucicula (W.Smith) Donkin (B) and Cymbella affinis Kutzing (FB) in 108-88 cm, then to Diploneis crabro Ehrenberg (MB), Navicula palpebralis W.Smith (M), and Navicula ramosissima Cleve (BM) in 88-85 cm. All these species are planktonic, except Navicula ramosissma Cleve (BM). It is therefore suggested that the domination of planktonic marine and brackish species coincides with the accumulation of Phragmites turfa, and is related to the upper limit of marine influence, i.e. the upper limit of the intertidal zone. The alternating changes in frequency of planktonic M and MB species, planktonic B species, and BF-FB-F species represent a slightly fluctuating water level. The obvious occurrence of benthonic brackish-marine species in the upper contact of the Phragmites sequences indicates a rise in sea level which might exceed the deposition of the Phragmites sequences.

4.4.3. Diatoms from the basal peat samples

Examination of diatoms for the basal peat samples and the clastic sediments above and below the basal peat were carried out during the present study. Fifteen samples from boreholes M1, M2, M3, and M5 (Heysham Harbour), C6 (east of Morecambe Bay), and B1, C8, A5 and C7 (the lower Leven Estuary) were prepared (Appendix III, ADDITION).

In order to examine the clastic sediments below the basal peat, three samples of grey-blue silty and clayey fine sand in borehole M3 from -20.36 to -21.26 m O.D., about 2 m below the basal peat, were prepared for diatom analysis. However, no diatoms are found from these samples.

For the basal peat, eight samples were examined. Of which, no diatoms are found in the samples in boreholes M1, M2 and B1. However, there are a great number of diatoms found in the peat samples in boreholes C8, A5, C7 and C6. In Heysham Harbour, the basal peat contains no diatoms but extremely high frequencies of Sphagnum and Filicales spores (pollen data from M.J. Tooley). This may suggest that the basal peat in Heysham Harbour was a bog or carr deposit. In contrast, in the peat in borehole C6 about 2 kilometre offshore in east Morecambe Bay, the diatoms are mainly of planktonic marine and marine-brackish species. Such a diatom group represents an upper intertidal environment, eg. a saltmarsh. Along the lower Leven estuary, diatoms identified from the peat samples in boreholes C8, A5 and C7 are dominantly of fresh and fresh-brackish water species (Fig. 4.13.), with low frequencies of brackish and marine-brackish species. These diatom groups may also represent an upper intertidal environment, and the peat is possibly a saltmarsh deposition. Compared with the diatom group in borehole C6, the peat deposition in boreholes C8, A5 and C7 had a stronger influence from fresh water which might come from the rivers feeding into the estuary. Looking closer at the diatom groups in boreholes C8, A5 and C7, one can find that there are much more fresh and fresh water species and less marine and brackish species in the up-estuary site (C7) than in the down-estuary site (C8).

The clastic sediments above the basal peat are mainly marine in origin. For example, two samples of silty clay in borehole M1 (-14.17 and -15.60 m O.D.) immediately above the basal peat contain dominant marine and marine-brackish species of diatoms (Fig. 4.13.) and low frequencies of fresh-brackish and brackish-fresh species. At a higher altitude, two silty clay samples in boreholes M3 (-11.28 m O.D.) and M5 (-8.99 m O.D.) also contain diatoms of marine and brackish species.

4.5. Pollen Analysis

Eighty-nine samples from two boreholes of PC-1 and PIT2C and two pits of PIT1 and PIT2 were pollen counted. Results of the counting are introduced and the local pollen assemblage zones (LPAZ) are discussed in the following sections. In the following sections, TTP means total tree pollen, TLP means total land pollen and TP means total pollen and spore.

For each level, land pollen were counted for up to 200 grains, except for the levels in Stratum 3 in borehole PC-1. In Stratum 3 of borehole PC-1, only 150 land pollen grains were counted due to the bad preservation of pollen. In most cases, tree pollen were counted for around 100 grains. In Figures 4.14-20, tree taxa are presented as percentages of total tree pollen. Shrub and herb taxa are presented as percentages of total land pollen. Aquatic taxa and spores are presented as percentages of total pollen.

4.5.1. PC-1

In borehole PC-1, 40 levels sampled from the five organic strata (Strata 3, 6, 13, 15 and 17 in Fig. 4.8.) were pollen analyzed. The results are displayed in Figures 4.14 - 17.

In Stratum 3, pollen from nine levels are counted and grouped into one LPAZ, PC-1-A (Fig. 4.14.). In this zone, Pinus (55.4-77.9 percent of TTP) dominates throughout, accompanied with relatively high frequencies of Corylus (6.6-16.7 percent of TLP), Quercus (5.3-26.5 percent of TTP) and Betula (6.3-18.5 percent of TTP). Ulmus increases considerably from 2.2 percent of TTP at level 429 cm to 11.9 percent of TTP at level 423 cm. No Alnus is found in this zone. Gramineae varies from 3.3 to 10.0 percent of TLP, and Cyperaceae, from 6.6 to 14.0 percent of TLP. Chenopodiaceae is found throughout the zone, coincided with high frequencies of Typha angustifolia, suggesting that this layer of fine organic sediments was deposited possibly at upper part of intertidal zone.

In Strata 5-6, seven levels of pollen samples were examined (Fig. 4.15.). The pollen assemblages identified are divided into two LPAZs, PC-1-B and PC-1-C. Pollen assemblages of the lower three levels from 309, 307 and 305 cm is grouped into zone PC-1-B. Samples of these three levels are obtained from the upper part of Stratum 5 which is of organic silty clay, a transition layer. This pollen zone is featured by the dominant tree and shrub pollen. The frequencies of Pinus (26.7-37.8 percent of TTP), Quercus (20.8-32.5 percent of TTP) and Betula (19.3-29.2 percent of TTP) are relatively high. But Corylus (35.5-38.0 percent of TLP) is the dominant pollen type in this zone. Ulmus maintains its frequencies of around 8.3-13.3 percent of TTP. Alnus occurs at this zone although its frequencies are low (3.3-7.6 percent of TTP). In zone PC-1-C, four levels of pollen assemblages are examined from Stratum 6 which is Phragmites turfa. In this zone, Corylus (26.5-31.1 percent of TLP) and Quercus (40.9-49.0 percent of TTP) dominate throughout, whilst Pinus (11.4-27.3 percent of TTP) and Ulmus (5.7-7.9 percent of TTP) slightly decline. Betula (21.1-26.3 percent of TTP) maintains its frequencies as it is in zone PC-1-B. Alnus increases from 7.0 percent at level 303 cm to 11.4 percent of TTP at level 302 cm, but decreases upwards to 2.3 percent of TTP at level 300 cm. The remarkable increases in Gramineae, Cyperaceae and Chenopodiaceae as well as the occurrence of Plantago maritima are the most important feature of this zone, suggesting a sedimentary environment of saltmarsh as the stratigraphy indicates.

In Strata 13 and the lowest part of Stratum 14, pollen assemblages of six levels are grouped into a PLAZ, PC-1-D (Fig. 4.16.). In this zone, the dominant pollen types include Corylus (18-25.6 percent of TLP), Quercus (29.1-40.0 percent of TTP) and Betula (21.1-31.3 percent of TTP). The secondary dominant pollen types comprise Pinus (12.1-21.4 percent of TTP), Alnus (8.7-17.0 percent of TTP) and Ulmus (7.4-12.6 percent of TTP). Cyperaceae (10.0-16.0 percent of TLP) changes little throughout the zone. Gramineae increases upwards from 3.0 to 12.8 percent of TLP, whilst Chenopodiaceae decreases from 12.5 to 3.5 percent of TLP).

In Stratum 15, four levels of pollen assemblages are divided into two LPAZs, PC-1-E and PC-1-F1. In zone PC-1-E, Quercus (45.2-57.9 percent of TTP) dominates, with relatively high frequencies of Corylus (15.0-17.4 percent of TLP), Alnus (15.9-21.2 percent of TTP) and Betula (15.8-21.2 percent of TTP). Frequencies of Pinus (2.2-6.6 percent of TTP) and Ulmus (3.9-7.8 percent of TTP) become very low. Frequencies of Gramineae are still relatively high (13.5-17.9 percent of TLP), whilst Cyperaceae decreases from 26.5 to 9.0 percent of TLP). In zone PC-1-F1, however, the sharp rise in Alnus pollen (59.1 percent of TTP) is remarkable. Frequencies of Corylus (10.5 percent of TLP), Quercus (19.5 percent of TTP) and Betula (15.4 percent of TTP) remain relatively high. Frequencies of other pollen types are low.

In Stratum 17, fourteen levels of pollen assemblages are divided into three LPAZs (Fig. 4.17.). In zone PC-1-F2, Alnus (32.3-39.6 percent of TTP) and Quercus (24.8-35.4 percent of TTP) are dominant, associated with relatively high frequencies of Corylus (11.0-15.5 percent of TLP), Betula (17.1-19.8 percent of TTP) and Pinus (8.1-14.8 percent of TTP). Ulmus decreases from 5.9 to 1.8 percent of TTP. Gramineae (11.0-15.5 percent of TLP) and Cyperaceae (10.0-18.0 percent of TLP) maintain relatively high, associated with occurrence of Chenopodiaceae and Plantago maritima.

In general, zone PC-1-F3 is more or less similar to zone PC-1-F2 (Fig. 4.17.). The major differences comprise that, in PC-1-F3, there are fewer Pinus, Ulmus, gramineae and Cyperaceae but more herbaceous pollen of dry-land species. In PC-1-F4, Alnus (43.1-71.1 percent of TTP) is still dominant, with relatively high frequencies of Corylus (17.0-19.4 percent of TLP), Quercus (17.5-30.2 percent of TTP) and Betula (9.3-21.1 percent of TTP). Gramineae (11.0-22.9 percent of TLP) increases remarkably, associated with the occurrence of Chenopodiaceae and Plantago maritima.

4.5.2. PIT2 and PIT2C

In PIT2 and the extension PIT2C, 26 samples from the three organic strata were examined. The pollen assemblages identified are plotted in Figures 4.18-19.

In PIT2C (Fig. 4.8.), fourteen levels of pollen samples were analyzed

(Fig. 4.18.). Results of the analyses suggest three LPAZs which are identified from the pollen assemblages. Zone PIT2C-A is featured by high frequencies of Pinus (55.4-59.1 percent of TTP), associated with Corylus (14.4-15.5 percent of TLP), Quercus (17.3-17.7 percent of TTP) and Betula (14.2-16.9 percent of TTP). Ulmus (7.9-8.5 percent of TTP) is relatively high, whilst Alnus (1.5-1.6 percent of TTP) is low. Cyperaceae (15.5-15.9 percent of TLP) dominates the herbaceous pollen group.

In zone PIT2C-B, Pinus decreases upwards from 39.0 to 11.0 percent of TTP, whilst Betula increases from 14.3 to 35.0 percent of TTP. Corylus (23.3-27.9 percent of TLP) and Quercus (30.5-37.0 percent of TTP) remain constantly high frequencies. Ulmus declines slightly from 13.3 to 6.0 percent of TTP, whilst Alnus increases from 2.9 to 11.0 percent of TTP. Cyperaceae too declines slightly from 14.4 to 7.0 percent of TLP, whilst Gramineae increases from 7.9 to 15.4 percent of TLP. Typha angustifolia increase up to 5.5 percent of TP, associated with occurrence of a few Chenopodiaceae and Plantago maritima.

In zone PIT2C-C, Pinus increases from 13.3 to 46.7 percent of TTP, whilst Betula decrease from 30.9 to 13.3 percent of TTP and Quercus too decreases from 38.9 to 15.5 percent of TTP. Corylus (around 19.0 percent of TLP), Alnus (around 11.0 percent of TTP) and Ulmus (around 8.0 percent of TTP) remain constantly. Cyperaceae increases slightly from 8.9 to 18.0 percent of TLP. The most important feature of this zone is the high frequencies of Gramineae which increase from 20.7 at the bottom to 33.8 percent of TLP at the middle of the zone, then decrease to 16.0 percent of TLP at the top of the zone. Such high frequencies of Gramineae seems to associate with the deposition of Phragmites turfa in Stratum 3. Typha angustifolia, Plantago maritima and Chenopodiaceae occur throughout the zone.

In PIT2, twelve levels are prepared from Strata 2-6 and 8-9 (Fig. 4.8.) for pollen analysis. Results of the pollen analysis suggest that the pollen assemblages could be divided into three LPAZs (Fig. 4.19.).

In Strata 2-6, seven levels of pollen assemblages are grouped into one zone, PIT2-D. This zone is characterized by the high frequencies of Quercus (36.9-49.6 percent of TTP), Corylus (24.0-12.5 percent of TLP) and Betula (14.8-27.3 percent of TTP). Alnus increases from 6.6 to 17.3 percent of TTP, but decreases slightly further upwards. Ulmus frequencies are low, ranging between 1.8 and 5.4 percent of TTP. At levels 120 and 85 cm, Pinus frequencies are high. However, these Pinus grains might not totally come from local pollen rains but follow water flows into the sampling site. Apart from these two levels, Pinus declines upwards from 22.8 to 12.3 percent of TTP. Gramineae (13.7-31.3 percent of TLP) dominates the herbaceous group, except for the top and bottom levels. Cyperaceae remains low frequencies (around 6.5-8.5 percent of TLP) but increases up to 14.5 percent of TLP at the top level. Chenopodiaceae and Typha angustifolia occur throughout the zone whilst Plantago maritima is found at the bottom and upper levels.

Levels at 35 and 25 cm are grouped into zone PIT2-E. It should be indicated that the assemblage at level 35 cm may have been affected by water inflows. The Pinus in particular might have been partly transported into the site by water currents other than by local pollen rain . Apart from these uncertainties, this zone (according to level 25 cm) is featured by high frequencies of Corylus (21.5 percent of TLP), Quercus (44.6 percent of TTP) and Alnus (30.7 percent of TTP). Betula (14.9 percent of TTP), Gramineae (12.5 percent of TLP) and Cyperaceae (10.0 percent of TLP) are the secondary dominant taxa. Pinus and Ulmus are very low (6.0 and 4.0 percent of TTP respectively).

The first important feature of zone PIT2-F1 is the high frequencies of Alnus (45.6-57.8 percent of TTP), associated with high frequencies of Filicales, suggesting an alder carr not far from the sampling site. The second important feature of this zone is the decline in Ulmus pollen from 3.4 to 1.0 percent of TTP). Other dominant taxa in this zone include Corylus (19.0-22.5 percent of TLP), Quercus (23.3-32.2 percent of TTP), Betula (12.9-21.1 percent of TTP). Gramineae and Cyperaceae are also relatively high (13.5-16.0 and 6.0-14.0 percent of TLP respectively).

4.5.3. PIT1

Twenty-three samples from PIT1 were collected for pollen analysis. Results of the pollen counting (Fig. 4.20.) suggest that the pollen assemblages identified should be divided into three LPAZs. The lowest five levels of pollen assemblages are grouped into zone PIT1-F2. In this zone, Alnus increases slightly from 26.8 to 42.3 percent of TTP, whilst Quercus decreases from 34.1 to 21.1 percent of TTP. Corylus (13.9-18.5 percent of TLP) and Betula (23.9-29.2 percent of TTP) remain their relatively high frequencies throughout the zone. Frequencies of Ulmus are low throughout the zone varying between 4.9 and 1.4 percent of TTP). Gramineae (10.9-23.0 percent of TLP) and Cyperaceae (10.0-14.4 percent of TLP) are the dominant taxa in herbaceous group. Low frequencies of Chenopodiaceae, Plantago maritima and Typha angustifolia occur throughout the zone. Filicales are high, associated with the high frequencies of Alnus.

In zone PIT1-F3, Alnus decrease from 52.2 to 39.4 percent of TTP, whilst Corylus increases from 25.0 to 43.1 percent of TLP and Quercus from 14.8 to 27.2 percent of TTP. Betula remains its relatively high frequencies (25.6-34.6 percent of TTP). Ulmus declines again, coincided with the sharp decrease in tree pollen at the top level. As shrub pollen increase, Gramineae and Cyperaceae decrease slightly from 16.5 to 6.0 and from 9.0 to 3.5 percent of TLP respectively. A few Chenopodiaceae, Plantago maritima and Typha angustifolia are still found in this zone. Filicales decline sharply, indicating a change in local vegetation from Alder carr to bog.

The other thirteen levels are grouped into zone PIT1-F4. Apart from the decline in Betula, Corylus (15.8-37.1 percent of TLP), Alnus (26.5-66.7

percent of TTP) and Quercus (27.8-47.3 percent of TTP) dominate the zone. One remarkable feature of this zone is the high frequencies of Ericales (34.2 percent of TLP at its peak). Gramineae and Cyperaceae are low but increase at the upper levels. Other herbaceous pollen include Caryophyllaceae and Plantaginaceae. In the upper levels, Sphagnum is relatively high.

4.5.4. Regional pollen assemblage zones

Comparison between PC-1, PIT2 and PIT1 has been made. Some major points come out from the comparison and are illustrated as follows.

1. Both zones PC-1-A and PIT2C-A are marked by high frequencies of Pinus, accompanied with dominant Corylus and Quercus.

2. Features of zones PC-1-B and PIT2C-B include the decline in Pinus, occurrence of Alnus, high frequencies of Corylus, Quercus and Betula, and relatively high frequencies of Ulmus.

3. In zones PC-1-C and PIT2C-C, Corylus and Quercus still dominate, accompanied with an increase of Alnus. Pinus increases but Betula decreases. The most important feature of these two zones is the high frequencies of Gramineae, which associated with the deposition of Phragmites turfa at both sites.

4. Zones PC-1-D and PIT2-D are dominated by Corylus, Quercus and Betula. The secondary dominant taxa include Alnus and Pinus. Frequencies of Ulmus are much lower than those in zones PC-1-C and PIT2C-C, suggesting the commencement of the primary decline in elm pollen. Frequencies of Gramineae, Chenopodiaceae, Plantago maritima and Typha angustifolia suggest a saltmarsh environment.

5. Features in assemblage zones PC-1-E and PIT2-E are more or less similar to those in zones PC-1-D and PIT2-D. The major differences include the lower frequencies of Pinus, the higher frequencies of Alnus and the high frequencies of Filicales.

6. Zones PC-1-F1 and PIT2-F1 are marked by the rapid increase in Alnus pollen and the first decline in Ulmus pollen.

7. In zones PC-1-F2 and PIT1-F2, frequencies of Alnus are slightly lower than those in zones PC-1-F1 and PIT2-F1. Apart from this, the frequencies of Corylus, Quercus, Betula, Gramineae, Cyperaceae and Filicales are still relatively high. Ulmus maintains its low frequencies throughout the zones.

8. Zones PC-1-F3 and PIT1-F3 is marked by the secondary decline of Ulmus. Other features include the high frequencies of Alnus, Corylus, Quercus and Betula.

9. The main feature of PIT1-F4 is the dramatic increase of Ericales, whilst no such indication is suggested from zone PC-1-F4, due to the difference in sedimentary environment between these two sites.

4.6. Chronological Analysis

A chronology of Flandrian deposition could be established by direct radiocarbon dating of the organic sequences and by comparing the local pollen assemblage zones with the well-established regional pollen zones as a cross check. In the present study, both methods are applied to date the Flandrian sedimentary sequences in Skelwith Pool.

Eight samples were collected from borehole PC-1 and an excavation PIT2 in Skelwith Pool (Fig. 4.8.), and radiocarbon dated by the Godwin Laboratory, Cambridge. Comparison of the local pollen assemblage zones from Skelwith Pool with those published and radiocarbon dated from areas adjacent to Morecambe Bay has been made. The radiocarbon dated ages are listed in Table 4.1. and assessed as follows.

SP-1 The high frequencies of Pinus in the local pollen assemblage zone PC-1-A can be dated to late Flandrian Id around 7460±150 B.P., referring to zone d at Red Moss (Hibbert et al., 1971) and zone RM.5 in Rusland Valley (Dickinson, 1973; Tooley, 1987b). The date of 7875±85 B.P. seems to be a little older. However, with a two standard deviation in age, this date is acceptable.

SP-2 The end of the sharp drop in Pinus pollen in zone PC-1-B could be dated to shortly after 7107±120 B.P. (Hibbert et al., 1971). A sharp decline in Pinus pollen also occurred at the same time in Nant Ffrancon, north Wales (Hibbert and Switsur, 1976) and Somerset Levels (Beckett and Hibbert, 1979). The date of 7150±80 B.P. is good.

SP-3 The commencement of the primary elm-decline was dated to 5750±90 B.P., relating to the event at the end of zone RW-1 in Roudsea Wood (Birks, 1982). Similarly, the commencement of the elm-decline was dated to 6010±100 B.P. at Din Moss (Hibbert and Switsur, 1976), and

Table 4.1. The radiocarbon dates from Skelwith Pool

Sample Ref.*	Material	Thickness cm	Altitude m O.D.	Lab. Ref.	C-14 years B.P.
SP-1	$Sh^2$2,$Dl^2$1,As1	10	0.57±0.05	Q-2782	7875±85
SP-2	$Th^2$2(Phrag.),$Dh^2$2	4	1.79±0.02	Q-2783	7150±80
SP-3	$Th^2$3(Phrag.),$Dh^2$1	2	3.63±0.01	Q-2784	5660±55
SP-4	$Th^3$3(Phrag.),$Dh^2$1	2	3.77±0.01	Q-2785	5430±50
SP-5	$Th^3$3(Phrag.),$Dh^2$1	2	3.83±0.01	Q-2786	5130±65
SP-6	$Th^2$3(Phrag.),$Dh^2$1	4	3.93±0.02	Q-2787	4980±55
SP-7	$Th^3$2(Phrag.),$Dh^2$1	2	4.57±0.01	Q-2788	4710±75
SP-8	$Sh^3$3,$Th^2$1	6	4.45±0.03	Q-2789	3945±75

* see Figure 4.8.

5770±90 B.P. in Upper Teesdale (Turner et al., 1973). The date of 5660±55 B.P. is therefore acceptable.

SP-4, 5 and 6 These dates should fall in the course of the elm-decline, with particular pollen features of dominant Quercus and Corylus and dramatic increase in Alnus. They were expected to be around 5600-5000 B.P. The dates of 5430±50, 5130±65 and 4980±55 are very close to those expected and therefore acceptable.

SP-7 The end of the first elm-decline has been dated to 5010±80 B.P. at Red Moss (Hibbert et al., 1971). The end of the elm-decline was also dated to 5390±70 B.P. in Din Moss (Hibbert and Switsur, 1976), 5220±120 B.P. in Upper Teesdale (Turner et al., 1973), 5050±70 B.P. in Nant Ffrancon (Hibbert and Switsur, 1976), and 4657±55 B.P. in Somerset Levels (Beckett and Hibbert, 1979). The date of 4710±75 B.P. is a little younger than expected but still acceptable.

SP-8 The date 3945±75 B.P. is related to the secondary elm-decline.

The second decline in elm pollen has been dated to 3870±70 and 3597±70 B.P. at Foulshaw Moss, Morecambe Bay (Wimble, 1986). This event was also dated to 3604±45 B.P. at Somerset Levels (Beckett and Hibbert, 1979).

4.7. Stratigraphic Development

On the basis of the studies demonstrated in the previous sections, the history of stratigraphic development in Skelwith Pool is reconstructed. From the history reconstructed, a stratigraphic model is established in a regional scale, referring to Leven Estuary and Morecambe Bay.

4.7.1. Stratigraphic development in Skelwith Pool

Linking up the sedimentary sequences between boreholes is the first task to produce a full picture explaining the changes in sedimentary environment. There are four normal routines to complete this task: depositional correlation, altitudinal correlation, chronological correlation, and bio-stratigraphical correlation. Of these, the depositional and altitudinal correlations are common. These approaches concentrate on linking up the layers with similar sedimentary facies and at similar altitudes. However, results of these approaches do not provide information of iso-time depositional processes, due to the fact that sedimentary facies could vary from site to site on an iso-time depositional surface. Chronological correlation can avoid this disadvantage, but a sufficient number of dates are needed. Bio-stratigraphical correlation, derived from results of pollen analysis for instance, seems to be an alternative way to complete this task. In order to examine the relationship between sea-level changes and coastal responses, which is one of the aims of the thesis, processes of change in the coastal environment or sedimentation should be emphasised. Therefore, bio-stratigraphical correlation is applied in the present study for linking up stratigraphy between boreholes.

Based on the stratigraphic survey, the pollen and diatom analyses, and the chronological analysis described in the above sections, the stratigraphy of Skelwith Pool can be summarised by linking up the sedimentary sequences (Fig. 4.21.). For instance, Strata 8-9 in PIT2, and Stratum 15 in PC-1 can be linked together as these levels were formed close to time of the end of the first elm-decline and are characterised by a dramatic increase in alder pollen.

From Figure 4.21., the history of stratigraphic development in Skelwith Pool is reconstructed. A few significant points with the history should be emphasized.

Before 7875 B.P., Skelwith Pool had been inundated by brackish water. As a result, intertidal clastic sediment of over 3.5 m in thickness was deposited in the area. Around 7875 B.P., however, there was a short period of fine organic deposition in the area between Bore PC-1 and Bore 4. In Strata 1-3 of Bore PC-1, the sedimentation changes from silts to silty clay, then to organic material with many Chenopodiaceae and aquatic pollen, coincided with an increase in planktonic marine and brackish diatoms and decrease in benthonic marine and brackish diatoms. These changes suggest that the sedimentary environment in the site had changed from lower intertidal zone to upper intertidal zone.

Shortly after 7875 B.P., brackish water regime dominated Skelwith Pool again. During the period from 7800 to 7150 B.P., there was another cyclic change in the area from lower intertidal zone to upper intertidal zone, supported by pollen, diatom and stratigraphic evidence. Around 7150 B.P., Phragmites turfa dominated the organic deposit, and there was a thin layer of gyttja underneath the Phragmites deposit. This Phragmites deposit occurs over a relatively large area between Bores 13 (seawards) and 12 (landwards).

During the period of 7150-5660 B.P., Skelwith Pool was inundated again, allowing intertidal silts and clay to overlie on the Phragmites deposits in the area. Since 5660 B.P., the area landwards from Bore 4 has emerged gradually as a process from saltmarsh/Phragmites reedswamp to raised bog, while sedimentation of intertidal silts and clay in the area seawards from Bore 7 has remained. During the period of 5660-4710 B.P., however, the central area between Bores 4 and 7 was inundated for several occasions, which allowed alternating deposition of saltmarsh/reedswamp and intertidal silty clay. According to the diatom analysis, the marine influence in Skelwith Pool was still very strong during this period. Furthermore, one of the marine inundations between 4980 and 4710 B.P. extended deposition of silty clay landwards to

Bore 18. About 3950 B.P., the <u>Phragmites</u> swamp in the area landwards from Bore 4 was dried out, and a raised bog grew upon it.

Saltmarshes might have remained in, or sea water has occasionally inundated over, the area seawards from Bore 14 since then. But this area has been reclaimed by local people for keeping sheep for at least the last two centuries (data from Holke Estate Office). At present, the ground surface of the land reclaimed varies between 5.4 and 4.6 m O.D., about 0.3-1.1 m lower than the level of the local Highest Astronomical Tide and just around the local Mean High Water Spring Tide (see Table 7.1.). In Skelwith Pool, therefore, there is no evidence indicating marine inundation at an altitude higher than 5.4 m O.D.

4.7.2. Stratigraphic model

Combining all lines of evidence, a summarized model of stratigraphic development along the Leven estuary is established (Fig. 4.22.). Before any further investigation, this model is, in this thesis, hypothetically referred to the whole Morecambe Bay. From this model, the Flandrian process of coastal stratigraphy can then be summarized and divided into four units.

<u>Unit I. Alluvial/Lacustrine Deposit and Basal Peat.</u>

The alluvial/lacustrine deposit, with a layer of compacted peat (0.10-1.22 m in thickness) on top of it, is underlaid by till (Figs 4.2 and 4.5.). In

Heysham Harbour, the peat is a Sphagnum raised bog deposit, and deposited during the period of from 9270±200 to 8925±200 B.P at an altitude from -17.60 to -16.04 m O.D. (Tooley, 1987b). This period was followed by a rapid marine inundation and silty clay deposition of intertidal facies. On offshore sites, possibly along the lower Kent Estuary and along the lower Leven Estuary in particular, the peat is of saltmarsh in origin. This peat deposited during the period from 8740±65 to 8330±125 B.P. at an altitude from -16.7 to -15.9 m O.D., possibly associated with the earliest stage of Flandrian marine inundation.

Unit II. Major Marine Sequence.

This unit comprises dominant intertidal minerogenic sediments which were filled into the Bay during the period from 7995 to about 5660 B.P. Around the heads of the estuaries, the Leven estuary for example, this unit was intercalated by two or three thin beds of organic (gyttja or saltmarsh) deposits which are dated to about 7875-7750, 7100 and 6790 B.P. The upper altitudinal limit of this unit is up to about 3 m O.D. in up-estuary sites, at lower Rusland Valley for example (Dickinson, 1973; Tooley, 1987b), the Roudsea Wood (Birks, 1982), and Skelwith Pool. During this period, sea water occupied an area in the Bay much more extensive than that in the present day, including most of the present coastal mosslands. Saltmarshes and reeds were able to grow only in the far upstream sites, such as the Rusland Valley and Siverdale Moss.

Unit III. Secondary Marine Sequence.

This unit includes alternating intertidal minerogenic sediments and organic (saltmarsh, reeds and gyttja) deposits. This unit was deposited during the periods starting about 5660 B.P. and ending about 4980-4616 B.P., varying from up-estuary to down-estuary sites or from landward to seaward sites. Within this unit, the organic deposits are still relatively thin, about 0.20-0.60 m, but thicker than those within the unit II. The upper altitudinal limit of this unit is up to around 5.2 m O.D. in up-estuary sites. It is obvious that during this period, saltmarshes and reeds could colonise seawards and deposit in some mid-estuary sites, Skelwith Pool and Helsington Moss for instance.

Unit IV. Marine Regressive Sequence.

This unit is composed in onshore sites of dominant organic (from saltmarshes to weeds, then to carr or raised bog) deposits, which also form the features of the present coastal mosslands, like Deanholme Moss, Ellerside Moss, Foulshaw Moss, Helsington Moss, Arnside Moss, Siverdale Moss, Heysham Moss and Pilling Moss. While intertidal minerogenic deposits dominated in offshore sites and form the present intertidal zone. There are only three occasions of marine inundation recorded. The first is recorded at Skelwith Pool starting at 3945$\pm$75 B.P. at 4.45 m O.D. The other two are recorded from 3600$\pm$100 to 3370$\pm$120 B.P. at 6.2 m O.D. at Pilling Moss (Barnes, 1975) and around 1545$\pm$35 B.P. at 5.64 m O.D. from Arnside Moss

(Tooley, 1978a, 1987b). The top surface of these organic deposits ranges from 4.5-6.0 m O.D. along the south coast (Pilling Moss) to 7.0-9.0 m O.D. in the north part of the Bay.

CHAPTER V

FLANDRIAN SEA-LEVEL CHANGES AND COASTAL RESPONSES IN MORECAMBE BAY

In this chapter all the available sea-level data will be re-examined in terms of accuracy relating to their ages, altitudes and indicative meanings, in order to reconstruct the Flandrian history of sea-level changes, and to assess the responses of coastal sedimentation to the changing sea-level.

5.1. Flandrian Sea-level History in the British Isles

In the British Isles, the interaction of isostatic land movements and eustatic sea-level changes and their combination have always been the main concerns in mary studies of Flandrian sea-level history. For instance, on the basis of an investigation in the western Forth Valley, Scotland, Sissons and Brooks (1971) suggested a period of isostatic land uplift before about 8500 B.P. which exceeded the eustatic sea-level rise. They also indicated that, after 8500 B.P., the rapid melting of the great ice-sheets in North America and

Scandinavia had caused an eustatic sea-level rise to overtake the isostatically rising land, resulting in a transgression of 7 m in 1000 years. The rapid reduction in the rate of sea-level rises as the maximum of the postglacial transgression was approached, subsequently followed by regression, has indicated the isostatic factor became dominant again (Sissons and Brooks, 1971).

At a site on the northern side of the Tay estuary in Scotland, Smith et al. (1985) indicated a rapid initial sea-level rise and subsequently slowed before culminating at around 10 m O.D. between 6240±80 and 6030±80 B.P. In the lower Ythan Valley, northeast Scotland, Smith et al. (1983) suggested that a transgression at an altitude of 2.7 to 3.5 m O.D. began at about 6189±95 B.P. and ended some time prior to 4000±80 B.P. In Solway Forth, southwest Scotland, Jardine (1975) suggested that the Flandrian transgression continued in the eastern Solway Forth and in Wigtown Bay until later than 5000 B.P. The timing of the end of the main Flandrian transgression in Solway Forth seems to be later than that in eastern Scotland and similar to that in northeast Scotland.

In northwest England, Tooley (1978a) indicated a rapid rise in sea level around 7800-8000 B.P. followed by a fluctuating sea-level throughout the rest of the Flandrian. He (1982) also constructed twelve positive and twelve negative tendencies of sea-level movement for the area from Liverpool Bay to the south Fylde. In the northeast England, however, sea-level data are very sparse (Tooley, 1982).

In southwest England and Wales, Heyworth and Kidson (1982) indicated that no significant difference in sea-level rise is apparent between southwest England and Cardigan Bay and no evidence of sea-levels higher than the present is seen. The general pattern of sea-level rise in southwest England is similar to that in northwest England, with a rapid rise at around 8000 B.P. In southeast England, however, Shennan (1982) concluded a fluctuating rising sea-level for the last 7000 years. Only one significant drop in sea level is seen around 3000 B.P. In the Thames Estuary, a continuous and fluctuating rise in sea level was also indicated (Devoy, 1979).

Flemming (1982) attempted to model the Flandrian eustatic sea-level changes and to construct a map showing rates of vertical isostatic displacement of the crust over the U.K. The map suggests no significant subsidence occurred in the southern England and Wales. But in western Scotland, a rate of uplift of 2.5 metres/millennium is indicated, and 1.5 metres/millennium in Morecambe Bay. Shennan (1989), on the other hand, tried to decouple the isostatic factor from data of relative sea-level for different localities. In the uplift centre, Firth of Forth, Tay area, Moray Firth and Firth of Clyde for example, dominantly continuous uplift over 1 mm/yr is indicated. In the intermediate uplift areas such as northeast Scotland, Solway Firth and Morecambe Bay, a rate of 1 to 0.1 mm/yr is suggested. In Fenland and the Thames Estuary, however, the rate of subsidence is as high as over 1 mm/yr.

In short, a rapid rise in sea level during the early Flandrian has been indicated from many localities around the U.K. This was followed by a fluctuating rising sea-level for the last 7000 years. During the early Flandrian, 8000-7800 B.P. in particular, eustatic rise in sea level exceeded the uplift in Scotland. But again, the isostatic uplift factor dominated in central Scotland around 6000 B.P. and northeast and southwest Scotland around 5000 B.P. In contrast, southeast England has experienced a continuous subsidence.

5.2. Examination of Sea-level Index Points

In practice, transgressive and regressive overlaps are only two types of sea-level index point (Tooley, 1982; Shennan, 1982, 1983a), defined in section 2.4.2. In Morecambe Bay, there are 31 index points that are radiocarbon-dated transgressive and regressive overlaps. As suggested in Figure 1.2., some of the regressive overlaps are possibly not related to a falling water level. Examination for the regressive overlaps should therefore be more careful. In the following sections, one of the main efforts made is to classify the regressive overlaps into two types: one relative to a falling water level and another regarding to a slowly rising water level.

5.2.1. Sea-level index points from Skelwith Pool

In the present study, eight samples of organic sediment have been selected from PC-1 and PIT2 and radiocarbon dated by Dr. V.R. Switsur at the Godwin Laboratory, Cambridge. Chronological assessment to these dates has been carried out in Chapter IV, and the dates are listed in Table 5.1.

In order to date the lowest layer of organic deposits (Figs. 4.8. and 4.21.), SP-1 was selected from the whole of Stratum 3 from borehole PC-1. Stratum 3 is interpreted as gyttja according to the aquatic pollen derived from the stratum. Diatom analysis (Fig. 5.1.) indicates that the marine influence became weaker from Stratum 2 to the lower contact of Stratum 3, as a result of sufficient sediment supply and because of slowing down of a rising sea-level, or a combination of both. The site was infrequently inundated by sea water, which allowed the gyttja to be laid down. During the deposition of the gyttja, fresh and brackish water occupied the site, indicated by high frequencies of aquatic and saltmarsh pollen taxa (Fig. 5.1C.). Diatom results suggested that, after deposition of the gyttja, sea level rose at a rate which was higher than that of the gyttja deposition. Sea water at the site became deeper while Stratum 4 was laid down. In short, the depositional environment had changed from lower intertidal zone (Stratum 2) to upper intertidal zone (Stratum 3), then to subtidal zone (Stratum 4). These changes in depositional environment of the site may suggest a process of sea-level movement which rose first at a reduced rate and second at a faster rate. No indication of a fall sea-level is found from the stratigraphy and pollen and diatom results.

SP-2 was collected from Stratum 6 from PC-1, which is a layer of partly humified Phragmites turfa and detritus, underlaid by marine clay with Phragmites fragments (Stratum 5), overlaid by a thin layer of organic substance or gyttja (Stratum 7) which is succeeded upward by marine clastic sequences. Diatom analysis suggests (Fig. 5.1C.) that marine influence was strong during Strata 5 and 7 being laid down. Pollen results indicate a process of drying out of the site from Stratum 5 to Stratum 6 and a further marine inundation at Stratum 7. Stratum 6 is too thin, only 3 cm. The signal of a falling sea-level is very weak. Therefore, SP-2 might represent another period of sea level movement which is similar to that suggested by SP-1.

SP-3, SP-4, SP-5 and SP-6 were selected from the lower sequences of Phragmites peat in PIT2. This layer of peat is sandwiched by marine silty clay (Strata 1 and 7, Fig. 4.8.). The peat sequences are inserted by a thin clayey layer (Stratum 4) which is thicker in seaward boreholes (Bore 14 and 11). Pollen assemblages suggest the domination of saltmarsh and reedswamp communities throughout the sequences (Fig. 5.1B.). Marine diatoms decreases sharply from levels 125 cm to 108 cm whilst aquatic pollen increase from levels 120 cm to 108 cm. SP-3 might therefore not necessarily indicate a fall in sea level. A peak of marine diatoms between SP-4 and SP-5 is possibly relative to a rise in sea level. However, there is possibly another interpretation that the clayey layer (Stratum 4) and the associated marine diatom peak may be a result of a lateral movement of a tidal channel during the period of a slowly rising sea-level. SP-6, a transgressive overlap, is definitely relative to a rapidly rising sea-level.

SP-7 was collected from Stratum 8 in PIT2 in order to date the regressive overlap. It was recorded that the Phragmites turfa (Strata 8-9) is underlaid by marine clastic sediments. Pollen analysis (Fig. 4.19.) suggests a change upward from saltmarsh to reedswamp communities. In a litho-stratigraphic term, SP-7 represents a regressive overlap. However, there is no indication of a drop in sea level, because the continuation in reedswamp deposition further upward is recorded in PIT1 nearby and the accumulation of marine clastic sediments is suggested at a higher level on the seaward side by stratigraphic survey (eg. Bores 14 and 15).

SP-8 is composed of a well humified humous substance (not gyttja) with herbaceous rootlets, which is sandwiched by clayey silt containing marine and brackish species of diatoms. Frequencies of saltmarsh communities and aquatic pollen increase from the middle to the upper part of the organic sequences (Fig.5.1A.). At the levels above SP-8, marine diatoms increase whilst fresh water diatoms decrease.

5.2.2. Sea-level index points from Morecambe Bay

To date, in the area of Morecambe Bay, twenty-three radiocarbon dates with detailed stratigraphic descriptions and pollen analyses are available. They were collected from free-face excavations and boreholes by various researchers, and dated by different radiocarbon dating laboratories, but using the same half-life of 5570 years and giving one sigma intervals. They are listed in Table 5.1. The locations from which the data were collected are shown in Figures 4.1. and 4.3.

Recently, based on these radiocarbon dates, the history of Flandrian sea-level changes of the area was illustrated in a time-altitude plot by Tooley (1982, 1987b). This work was extensively used for other research , not only on coastal evolution (Tooley et al., 1988), but also on regional correlation and isostatic movement (Shennan, 1987a, 1989). However, this work does not consider the compaction of the organic deposits, and does not differentiate the types of dated samples in terms of their relationships to a water level. Therefore, it is necessary to re-assess these samples to produce a more acceptable result and make a comparison with the data from Skelwith Pool.

In Rusland Valley and the Leven Estuary, on the north side of Morecambe Bay, four sites have been investigated in detail. Tooley (1987b) recorded a transgressive overlap from a borehole (RV-1) at the Crams in the lower Rusland Valley (SD 3441 8627). The stratigraphic record (Fig. 4.4.) shows that a layer of very dark brown gyttja with monocots is underlaid by grey medium and coarse sands. It is overlaid by laminated silty gyttja, in which the upper contact is considered as a transgressive overlap. A sample from the monocot gyttja near the contact at -0.41±0.03 m O.D. was dated to 7750±100 B.P. (Har.3709). In the valley of Rusland Pool, Dickinson (1973)

Table 5.1. Sea-level index points from Skelwith Pool and Morecambe Bay

Location	Lab.code	Date B.P.	± 1σ ***	Alt. m O.D	±	Indic.*	Ref.**
Arnside Moss	Hv.3461	1545	35	+5.56	0.02	T	1
Lousanna 2B	Gak.2500	3370	120	+6.23	0.02	R	3
Lousanna 2B	Gak.2499	3600	100	+6.19	0.02	T	3
Skelwith Pool SP-8	Q-2789	3945	45	+4.45	0.03	T	
Heysham Moss	Hv.2920	4190	150	+4.49	0.02	R	1
Foulshaw Moss	Q-88	4616	112	+5.18	0.30	R	2
Skelwith Pool SP-7	Q-2788	4710	75	+4.57	0.01	Ra	
Moss Farm	Hv.4347	4830	140	+4.81	0.03	Ra	3
Skelwith Pool SP-6	Q-2787	4980	55	+3.93	0.02	T	
Lousanna	Hv.3052	4900	450	+4.42	0.05	R	3
Arnside Moss	Hv.3460	5015	100	+4.98	0.02	Ra	1
Skelwith Pool SP-5	Q-2786	5130	65	+3.83	0.01	Ra	
Helsington Moss	Q-85	5277	120	+4.88	0.30	Ra	2
Skelwith Pool SP-4	Q-2785	5430	50	+3.77	0.01	T	
Ellerside Moss	Hv.3844	5435	105	+3.72	0.02	Ra	4
Skelwith Pool SP-3	Q-2784	5660	55	+3.63	0.01	Ra	
Silverdale Moss	Q-256	5734	129	+2.80	0.15	T	5
Silverdale Moss	Q-261	5865	115	+3.85	0.15	R	5
Silverdale Moss	Q-260	6590	144	+3.55	0.15	Ra	5
Roudsea Wood	Q-2098	6790	100	+2.29	0.02	R	6
Skelwith Pool SP-2	Q-2783	7150	80	+1.79	0.02	Ra	
C7 (Bay)	Hv.3360	7725	95	-15.79	0.42	T	7
Rusland Valley	Har.3709	7750	100	-0.41	0.03	T	7
Skelwith Pool SP-1	Q-2782	7875	85	+0.57	0.05	Ra	
B1 (Bay)	Hv.3362	7995	80	-11.24	0.08	T	7
C6 (Bay)	Hv.3462	8330	125	-16.34	0.61	T	7
C8 (Bay)	Hv.3356	8685	175	-15.54	0.05	T	7
A5 (Bay)	Hv.3361	8740	65	-16.63	0.23	T	7
M2 Heysham Har.	Birm.140	8925	200	-16.04	0.23	T	7
M1 Heysham Har.	Birm.139	9195	155	-16.29	0.10	T	7
M3 Heysham Har.	Birm.141	9270	200	-17.60	0.07	T	7

* The definitions were made by Tooley (1987b) with T, transgressive overlaps and R, regressive overlaps. Ra means those regressive overlaps are related to a slowly rising sea-level.

** 1, Tooley 1987b; 2, Smith 1959; 3, Barnes 1975; 4, Oldfield and Stathum 1963; 5, Oldfield 1960, 1963; 6, Birks 1982; 7, Tooley 1974, 1978a, 1987b.

*** half life = 5570 years

also recorded a marine clay laid down at an altitude from -0.75 to +1.35 m O.D. during FId. In Roudsea Wood, at the head of the Leven Estuary, Birks (1982) put a bore down in a hollow (SD 3333 4822) connecting with a small stream running out to the estuary. It is recorded that a layer of blue-grey silty clay which contains marine dinoflagellate cysts, sponge spicules and Radiolaria fragments is overlaid by a fen peat. A sample of fen-wood peat just above stratigraphic contact was dated to 6790±100 B.P. (Q-2098). The altitude of the top surface of the borehole is levelled, during the present study, to +5.37 m O.D. from a bench mark at the main entrance of the Natural Reserve, so that the altitude of the dated sample is at 2.29±0.02 m O.D. At Ellerside Moss (SD 3350 4800), Oldfield and Statham (1963) recorded a reedswamp peat which is 56 cm in thickness and is underlaid by marine clay and overlaid by *Sphagnum* peat. The transition from reedswamp peat to *Sphagnum* peat occurred during the time between FII and FIII, marked by the main decline in elm pollen. A sample from the reedswamp peat immediately above the marine clay at +3.72±0.02 m O.D. was dated to 5435±105 B.P. (Hv.3844) (Tooley, 1987b). This regressive overlap need not be necessarily related to a fall in water level because of the continuous accumulation of the thick reedswamp peat above the sample dated.

In Foulshaw Moss on the north shore of the Kent Estuary (SD 3460 4830), Smith (1959) recorded that a layer of reedswamp mud is underlaid by marine clay and overlaid by *Sphagnum* peat. The contact between the reedswamp mud and *Sphagnum* peat was dated to early FIII. The whole layer of reedswamp mud at +5.18±0.30 m O.D. was dated to 4616+/-112 B.P. (Q-88) (Godwin and Willis, 1961). This date seems to be a bit younger than that estimated from pollen analysis (Smith, 1959). Further north in Helsington

Moss (SD 3470 4900), Smith (1959) reported that a layer of reedswamp mud, sandwiched by Sphagnum fen peat and detritus woody mud, accumulated in late FII. The whole layer of reedswamp mud at an altitude of +4.88±0.30 m O.D. was dated to 5277±120 B.P. (Q-85) (Godwin and Willis, 1961). The sedimentary sequences at point 6 in Foulshaw Moss vary upwards from marine clay to reedswamp mud and to Sphagnum peat, which can be easily identified as a regressive overlap. However, the sequences at point 3 in Helsington Moss vary upwards from marine clay to detritus woody mud which are characterised by fresh water aquatic pollen, then from reedswamp mud to Sphagnum peat. Hence, the reedswamp mud could be considered as a transgressive formation. Due to the whole layer of the reedswamp mud being radiocarbon dated, the date could be a date of not only a transgressive overlap, but also a regressive overlap.

In Arnside Moss on the south shore of the Kent Estuary, the northeast head of the Bay, a free-face pit (SD 4672 7895) was investigated and samples were collected for pollen analysis and radiocarbon dating, by D. Kerr in September 1966 (Tooley 1987b). The profile recorded shows that a peat bed from 0.67 to 1.44 m in depth is underlaid by marine clay and overlaid by sandy peat and inorganic sand. The lowest part of the peat bed is dominated by Phragmites with clay and pollen of Gramineae and many Chenopodiaceae. A sample was taken from 1.38 to 1.42 m with an altitude of +4.98±0.02 m O.D., and was dated by pollen analysis to late FII. Its radiocarbon date is

5015±100 B.P. (Hv.3460). The upper most part of the peat bed is composed of amorphous peat with dominant Alnus pollen and Filicales spores indicating an alder carr community. A sample was taken from 0.71 to 0.74 m at an altitude of +5.56±0.02 m O.D. and was dated to late FIII and to 1545±35 B.P. (Hv.3461). As suggested (Tooley, 1987b), this radiocarbon date could be a bit younger, because the sample is too close to the ground surface, which could have resulted in penetration by roots and young carbon.

In Silverdale Moss (SD 3460 4750), further landwards from Arnside Moss, Oldfield (1960a) reported that there is a layer of marine clay sandwiched between organic deposits. He also indicated that both boundaries above and below the marine clay were dated to early FII. Three samples from the profile were radiocarbon dated (Oldfield 1960a). The first sample from the lower peat below the contact at +2.80±0.15 m O.D. is detritus mud and was considered as fen peat and dated to 5734±129 B.P. (Q-256). Comparing the pollen diagrams from northwest England, Oldfield (1965, p255) indicated that "Sample Q256, giving a date of 3774±129 B.C., was based on fen peat contemporary with a late stage in the pine decline, and no evidence was detected for a hiatus between this sample and the underlying peat recording the pine maximum". The second sample from the upper peat immediately above the clay at +3.55±0.15 m O.D. is Phragmites peat and was dated to 6590±144 B.P. (Q-260). The third sample from the fen peat immediately above the Phragmites peat at +3.85±0.15 m O.D. was dated to 5865±115 B.P. (Q-261).

In Heysham Moss (SD 34239 46083) on the west side of Lune estuary, a woody peat without Phragmites overlying marine clay at +4.49±0.02 m O.D. was dated to 4190±150 B.P. (Hv.2920) (Tooley, 1978a, 1987b). In Heysham Harbour, there is a layer of hard dry peat, which is composed of herbaceous roots and leaves (re-examined during the present study) and contains high frequencies of Sphagnum and Filicales spores (pollen counts from Dr. M.J. Tooley). In the present study, this peat was re-examined for diatoms, but no diatoms were found in the peat (see Appendix III). According to the pollen and diatom analyses, this peat is therefore interpreted as a bog deposit. Stratigraphically, this peat is overlaid by marine silty clay, but underlaid by alluvial deposits and boulder clay (Tooley, 1978a, 1987b). A sample of the marine silty clay was collected immediately above the peat in Borehole M1, M3 and M5, and examined for diatom analysis during the present study. The diatoms are dominated by marine and marine-brackish species (Fig. 4.13. and Appendix III). In Borehole M1 (SD 39361 59890), the peat was recorded at an altitude from -15.63 to -16.92 m O.D. A sample from the middle of the peat bed at -16.29±0.05 m O.D. was dated to 9195±155 B.P. (Birm.139). In M2 (SD 39338 59881), a sample was collected also at -16.04±0.23 m O.D. from the middle of the peat bed (-15.19 to -16.79 m O.D.), and dated to 8925±200 B.P. (Birm.140). Similarly, in M3 (SD 39326 59909), a sample was collected from the upper part of the peat bed at -17.60±0.07 m O.D., and dated to 9270±200 B.P. (Birm.141).

On the south coast of the Bay, Barnes (1975) put a series of boreholes down in Lousanna, south of Pilling Moss. In one of these boreholes (Lousanna, SD 4160 4486), a yellow brown Phragmites peat at +4.42±0.05 m O.D., overlaid by woody carr peat and underlaid by marine clay, was dated to 4900±450 B.P. (Hv.3052). There is evidence of a major decline in elm pollen. In the same transect, another borehole (Lousanna 2B) was recorded: within the woody carr peat above the Phragmites peat, there is a thin layer of fen peat with many pollen Typha sp. and with Phragmites fragments at a height of from +6.17 to +6.23 m O.D. Barnes (1975) suggested this was an event of marine flooding. A sample from the top of this layer at +6.23±0.02 m O.D. was dated to 3370±120 B.P. (Gak.2500). Another sample from the base of this layer at +6.17±0.02 m O.D. was dated to 3600±100 B.P. (Gak.2499). At Moss Farm (SD 4451 4832), Barnes (1975) recorded that a yellow/dark brown Phragmites peat of 35 cm in thickness is overlaid by birch carr peat and underlaid by marine clay. A sample from the Phragmites peat immediately above the marine clay (4.81±0.03 m O.D.) was dated to 4830±140 B.P. (Hv.4347).

In the east part of the Bay, it was recorded from borehole C6 (SD 44869 66459) (about two kilometres offshore from the east coast), that a brown peat is underlaid by post-glacial lake deposit and overlaid by marine silty clay at an altitude from -15.73 to -16.95 m O.D. From pollen analysis (Tooley, 1978a, 1987b), the surface of the peat bed is similar to reedswamps, but the majority to fens. A bulk sample (about 20 cm) from the peat bed, 30 cm below the upper contact (data from Terresearch Ltd.), was dated to 8330$\pm$125 B.P. (Hv.3462). During the present study, a sample from the peat was examined for diatoms which are composed of marine, brackish and fresh water species (Appendix III). The upper part of the peat bed is therefore interpreted as saltmarsh deposits.

In the northwestern part of the Bay, along the lower Leven Estuary, a transect of boreholes was put down by Terresearch Ltd. in 1967 (Knight, 1977) (see Fig. 4.5.). This peat is overlaid by marine silt and sand, and underlaid by boulder clay and post-glacial lake deposit (Tooley, 1987b). In Borehole C7, located near the railway bridge over the estuary (SD 32209 77915), the peat was recorded as a hard/dry peat with shells and some stones (Tooley 1987b). A jar sample (10 cm long) from the upper part (15 cm below the upper contact) of the peat layer was dated to 7725$\pm$95 B.P. (Hv.3360) at an altitude of -15.79 $\pm$0.05 m O.D. In borehole A5, about two kilometres further south (SD 32937 76367), the peat was recorded at -16.40 to -17.01 m O.D., and a core sample (46 cm long, or -16.63$\pm$23 m O.D.) from the upper part of the peat bed was collected and dated to 8740$\pm$65 B.P. (Hv.3361). In borehole C8, about 5 kilometres south to the C7 (SD 33500 74649), the peat was recorded at -15.49 to -16.40 m O.D., and a jar sample (10 cm long, or -15.54$\pm$0.05 m O.D.) from the top of the peat layer was dated to 8685$\pm$175 B.P. (Hv.3356). In borehole B1, about 7.5 kilometres south to the C7 (SD 32089 71901), a laminated peat is buried below a layer of green sand and gravel with clay, siltstone and peat at -11.24±0.08 m O.D. This sample was dated to 7995±80 B.P. (Hv.3362). During the present study, samples from the peat in boreholes C7, A5 and C8 were examined for lithology and diatoms. The result indicates that these samples are of laminated herbaceous turfa containing diatoms of dominant freshwater and fresh-brackish species with some brackish and marine species (Fig. 4.13. and Appendix III). The upper part of the peat layer are therefore interpreted as a saltmarsh deposit. All these data points are interpreted as transgressive overlaps.

5.3. Correction for the Sea-level Index Points

Correction for the sea-level index points is regarded to their errors in age and altitude, indicative meanings and spacial variation in tidal levels.

5.3.1. Errors of sea-level index points

There are two sorts of error for sea-level index points, errors in altitude and age. These errors should be estimated before reconstruction of sea-level history.

Errors in altitude

Errors in altitude for each dated sample come from consolidation of sediments and sampling operation which includes levelling to a benchmark, accuracy of a benchmark to O.D., measurement of depth using different samplers, and sampling density.

For operational errors, Shennan (1982) has given a list of estimated errors affecting the measured altitude of special layers, based on his work in Bourne Fen, the Fenland. To date, there is no new estimation available for operational errors which occurred when sampling. Therefore, Shennan's estimates are basically applicable for the present study. But, it should be born in mind that the errors in measurement of depth - angle of borehole for example - may be larger than those estimated by Shennan (1982), because the boreholes in Skelwith Pool are deeper than those in Bourne Fen, the Fenland. Considering the cases in Skelwith Pool and Shennan's estimates, the total operational errors could be up ± 0.75 m for the basal peat and ± 0.50 m for the others.

Errors in altitude derived from consolidation of sediments are more difficult to estimate, because it varies from place to place (see the review in section 2.3.). For organic deposits, however, from MacFarlane's work (1965) and Jelgersma's summary (1961), it seems likely that: (a) within a relatively short time after a load is applied, the peat could be compacted very quickly with a value of consolidation as high as 50 percent. This situation could be applied in order to consider the peat deposits which are overlaid by a thin minerogenic deposit. This is similar to the peats in Skelwith Pool (except the top peat). (b) In the longer term, after a heavy load is applied, the consolidation of peat deposits could account for up to 90 percent of the total thickness of the peat layer (such as the basal peat under Morecambe Bay). As the upper peat overlies minerogenic deposits on the coasts of Morecambe Bay, they are over two or three metres in thickness, and some of them have been drained for over a hundred years, which could have caused them to be consolidated. But fortunately, sea-level index points only come from the lowest contacts, so that no error should needs to be corrected from this cause.

In the present study, an attempt is made to reconstruct the original altitude of basal peat under Morecambe Bay using a compaction rate of 50 percent. For the peat overlaid by thin marine silty clay, a rate of 30 percent is used. For instance, the altitude of SP-2 (Table 5.1.) should be corrected by using a compaction rate of 30 percent, so that the corrected altitude is 1.81 ± 0.03 m O.D. However, correction for the compaction or consolidation of minerogenic deposits could not be made in the present study.

Errors in age

Errors in age for each dated sample may stem from the sampling and dating processes. All dates resulted from radiocarbon dating laboratories are given a range of one deviation in age (Table 5.1.). However, the thicknesses of the dated samples vary from 3 cm to 46 cm. It should therefore be stressed that the age dated from a thin sample is more accurate than that from a thick sample, besides factors of penetration of young carbon and reworking of old carbon.

On the other hand, samples listed in Table 5.1. were collected from one of three stratigraphic positions: top or base of an organic layer, middle of an organic layer, and the whole organic layer. In the first situation, a sample was collected from the top or base of an organic layer. The date of the sample should represent the age of the end or the beginning of the organic accumulation. In the second situation, a sample was collected from somewhere around the middle of an organic layer. The date therefore suggests the age within the period of the organic accumulation. A date, if it is assigned as the age of the upper stratigraphic contact for example,should therefore be corrected by reducing a length of time taken for the organic accumulation from the level where the sample dated is collected to the upper contact of the organic layer. In this case, a rate of 0.16 cm/yr for fen-wood peat (calculated by Birks (1982) in Roudsea Wood National Nature Reserve) and 0.5 cm/yr for saltmarsh peat (measured by Harper (1979) in the New Marsh at Gibraltar Point, Lincolnshire) may be applied. In this way, the age of the upper contact of the peat in borehole M2 (8925 years B.P.) is calculated to be 8240 years B.P. In the third situation, the whole peat layer is dated as a sample. It is clear that the date is the mean age of the organic layer dated. The time length of the peat accumulation could theoretically be estimated by considering factors of consolidation and accumulation of the peat layer. However, this kind of calculation seems unnecessary for a thin peat layer.

5.3.2. Indicative meanings of sea-level index points

The dated samples in Table 5.1. have originated from four major types of organic deposit: saltmarshes, the reedswamps dominated by Phragmites fragments, fen peat, and gyttja with pollen grains of Chenopodiaceae and aquatic plants suggesting a brackish pool protected by saltmarshes from sea water. The indicative meaning, i.e. the relationship of dated samples to a water level, is assessed in the following paragraphs.

Gray and Scott (1987, p103) indicated that "salt marshes are confined to the upper 2.5 m of the very large tidal range in Morecambe Bay. This range of 9.5 m from MHWST to MLWST results in a highly unstable intertidal system. Strong southwest winds may raise the actual high tide level well above the predicted height, the highest recorded storm tide reaching 7.6 m a.O.D. on 8 October 1896. .... This highly dynamic tidal regime is an important factor in limiting the salt marsh to the upper levels". On the coasts around the bay, four major types of saltmarsh have been recognised (Gray and Scott 1987) on the basis of a combination of soil and vegetation data. They are **Pioneer zones, Low-level Salting, High-level Salting** and **Mature marshes**. In which, Gray and Scott (1987, p108) described that "at the highest elevations in the bay and , particularly, in the brackish areas of the upper estuary two basic types of mature marsh community may be found. The first are highly diverse species-rich communities generally occurring on rarely flooded sites and the second are communities largely dominated by a single species. ...... Characteristic species of the second type of mature marsh are Phragmites". They further indicated that mature marshes occur vertically from +5.3 to +6.6 m O.D. with a mean altitude of +5.6 m O.D. (about 0.8 m higher than local MHWST). The high-level salting with high silt, immature soils and high organics occur from +4.9 to +5.8 m O.D. with a mean altitude of +5.4 m O.D. This figure is about 0.6 m higher than local MHWST of the northern part of Morecambe Bay.

Combining the present tidal levels recorded from tide gauges within the Bay with Gray and Scott's work (1987), the indicative meaning of the dates from saltmarsh deposits could be estimated. A sample from high salting and saltmarshes could represent a height 0.6 m higher than local MHWST with a range of ±0.20 m. A reedswamp peat dominated by Phragmites should represent a height 0.8±0.30 m above local MHWST (Table 5.2.). However, Tooley (1978a, p20) has reported that "The rhizomes and rootlets of the Phragmites form a fibrous material of sandy peat, which is a distinctive facies of the high intertidal zone. This community occurs at a height of +4.0 metres O.D. which is 15 cm below MHWS at Formby". Shennan (1986b) has estimated that a Phragmites or monocotyledonous peat directly above saltmarsh deposit represents a height of 20±10 cm above MHWST; directly below saltmarsh, 20±10 cm below MHWST. Both examples at Formby (refering to Altmouth) (Tooley, 1978a) and the Fenland (Shennan, 1986b) suggest a relatively smaller difference between sediments and the local MHWST. The higher difference for the sediments and the local MHWST in Morecambe Bay may result from the greater tidal amplitude in Morecambe Bay.

It is not known at what level fen communities are maintained in relation to mean sea-level or MHWST, or whether there is any relationship between the level of ground water in the fen and sea-level (Tooley, 1978a). However, in the Morecambe Bay woodlands, the lower limit of the trees (Betula, Alnus and Quercus) and the shrub (Salix) falls between the level of HAT and a height midway between that of MHWST and HAT (Kidson and Heyworth, 1979). A similar value of estimates was suggested for the fen wood peat deposit in the Fenland, England (Shennan, 1986b). In Fenland, it was estimated (Shennan, 1986b) that a dated sample of fen wood peat is about 43$\pm$20 cm above MHWST if the sample is directly above Phragmites peat or saltmarsh deposit; and is around MHWST with 20 cm deviation if the sample is directly below Phragmites peat or salt marsh deposit.

In Scotland at the heads of some of the sea lochs on Mull, the relationship of the contemporary coastal plant communities to MHWST has been described (Gillham, 1957). On Loch Scridain, a mixed grass, sedge and rush community was recorded from 23 to 59 cm above MHWST, and was replaced from 59 to 83 cm above MHWST by a mixed moorland community with occasional shrubs. On both Loch Scridain and Loch Guin, within 15 metres of the shore, deep peats had accumulated and supported vegetation of Myrica and Molinia or Calluna vulgaris (Linné) Hull and Erica tetralix (Linné). These latter communities occurred no more than 96 cm above MHWST. In

Table 5.2. Relations between organic deposition and tidal levels in Morecambe Bay

Tide levels relative to O.D., in metres (source: Admiralty Tide Tables 1989)	HAT	MHWST	MTL
Ulverston (the Leven estuary)	5.72	4.60	dried-out in LW
Arnside (the Kent estuary)	6.10	4.90	dried-out in LW
Morecambe (the east coast)	5.70	4.60	0.33
Heysham (the principle tide gauge)	5.60	4.50	0.30
Fleetwood (the southwest coast)	5.30	4.30	0.08

Types of organic deposition and their relations with tidal levels
(source: Kidson and Heyworth, 1979; Gray and Scott, 1987)

Saltmarsh deposit	0.60±0.2 m above MHWST
Phragmites deposit	0.80±0.3 m above MHWST
Fen wood deposit	0.25±0.2 m below HAT or above HAT

Indicative meanings of the dated samples

	range	water level
Saltmarsh (laminated) peat:		
directly above marine clastic deposit	40 cm	MHWST + 60 cm
directly below marine clastic deposit	40 cm	MHWST - 20 cm
Phragmites peat:		
directly above saltmarsh deposit	60 cm	HAT - 30 cm
directly above marine clastic deposit	40 cm	MHWST + 60 cm
directly below saltmarsh deposit	40 cm	MHWST
directly below marine clastic deposit	40 cm	MHWST - 20 cm
Fen wood peat:		
directly above Phragmites peat	50 cm	HAT
directly above saltmarsh deposit	50 cm	HAT - 25 cm
directly above marine clastic deposit	50 cm	HAT - 30 cm
directly below saltmarsh deposit	40 cm	MHWST + 20 cm
directly below marine clastic deposit	40 cm	MHWST - 20 cm
Gyttja:		
directly above marine clastic deposit	60 cm	MHWST + 30 cm
directly below marine clastic deposit	60 cm	MHWST - 60 cm

relation to mean sea-level, ground-water level and soil conditions, a succession from high saltmarsh, through reedswamp communities to shrub communities has been carefully recorded from Island Beach, New Jersey, by Martin (1959). Saltmarsh communities, dominated by Spartina patens, are maintained up to 34 cm above mean sea-level, and usually produce a peat 30 cm thick. Reedswamp communities, dominated by Typha and Phragmites, occur 122 cm above sea level, and are replaced by a shrub of Juniperus, Myrica and Rhus when the ground rises to 152 cm above mean sea-level.

All these studies in Morecambe Bay, the Fenland and Scotland (UK), as well as that in New Jersey (USA) suggest that fen communities can grow a bit lower than the highest limit of reedswamp or saltmarsh deposition, particularly when reedswamp or saltmarsh communities migrate seawards. On the other hand, a fen peat immediately above a reedswamp or saltmarsh peat might not suggest a height much higher than the upper limit of reedswamp and saltmarsh deposition. Therefore, the height of a fen deposit in Morecambe Bay may be just around the local HAT level.

It must be noted that saltmarsh, Phragmites and fen deposits directly below marine deposits - for example a fen-wood peat under marine deposits without a transition of Phragmites or saltmarsh deposits - should represent a height 0.2 ± 0.20 m below MHWST.

In the dates listed in Table 5.1., there are only two dates (SP-1 and No.16) which are dated from samples of gyttja. Gyttja is a Swedish name and is applied to a green-brown organic-rich sediment deposited in a lake (Lowe and Walker, 1984, pp 130). In the Crams of Rusland Valley, about 300 m south to Crooks bridge, borehole RV-1 reveals (Tooley, 1987b) that a layer of wet and very dark brown gyttja with monocots and very occasional wood fragments (the dated sample is collected from the upper part of this layer), is overlaid by slightly laminated silty gyttja of 3 cm in thickness, then by marine silt with roots of Phragmites. It suggests that the sedimentary conditions change from a fresh-brackish shallow pool to an open marine water. The dated sample deposited shortly before marine inundated, and therefore the surface contact of the gyttja could be very close to the MHWST mark. But, a gyttja deposit directly below marine deposits might represents a lower altitude, 0.6 ± 0.6 m below MHWST.

5.3.3. Variation in tidal range

It is well known that tidal range varies from one location to another. In fact, tidal range also varies through time (Woodworth et al., 1991). The Admiralty Tide Tables of 1989 reported that, in Morecambe Bay, the height of MHWST is 4.3 m O.D. in Fleetwood, 4.5 m O.D. in Heysham, 4.7 - 4.9 m O.D. in the Leven and Kent estuaries. It suggests that the variation of the height of the MHWST within the Bay is not minimal. In the present study, MHWST levels from every location, at where samples are collected, are therefore adjusted to that at Heysham Head, the principle tide gauge in Morecambe Bay. There is no correction for the dates from basal peat unit, because this sort of variation for the period of the early Flandrian marine inundation in the Bay is unknown.

The variation in tidal range through time has not been successfully estimated during the present study. Therefore, in the first instance, the present-day tidal range is applied to the whole Flandrian Age.

5.3.4. Correction for sea-level index points

Before reconstruction of the Flandrian sea-level history can be made, all the dated sea-level index points should be corrected or adjusted in age and altitude in terms of correcting the operating errors (Shennan 1982). Thereby, it is possible to estimate the original altitude and the age of stratigraphic contacts (distance from the dated sample to the contact of an overlap, and sediment compaction); to calculate the altitude relative to the MHWST (indicative meanings to tidal level); to define the overlaps (transgressive or regressive overlaps); and to average the inter-regional variation in tidal ranges.

In the present study, the date from borehole C7 (Tooley, 1987b) and the date (Q-256) from Silverdale Moss (Oldfield, 1960a) are much younger than they should be. The error range in age of the date from Lousanna (±900, two standard deviations) is too big. These three dates are not used in the present study. Dates from M1 (Birm.139), M2 (Birm.140) and C6 (Hv.3462) should be corrected to 8364±310 B.P., 8240±400 B.P. and 8216±362 B.P. respectively, for the ages of their upper stratigraphic contacts, the transgressive overlaps. It has been demonstrated that the rest of the dates seem to be more reliable and acceptable. The results of the correction in age associated with the altitudes (for the compaction) for the dates are listed in Table 5.3. Each date in Table 5.3. is also corrected for its altitude by adding a range of indicative meanings for each sample type, adjusting to the MHWST (4.5 m O.D.) at Heysham and adding operational errors (±0.75 m for the basal peats, and ±0.50 m for other samples).

Table 5.3. Correction for sea-level index points

No.	Date BP	±*	Alt.	m ±	Correcting values$ A	±	B	C	Corrected alt.	±
1	9270	400	-17.60	0.13	+0.20	0.20		0.48	-16.92	1.08
2	8740	130	-16.63	0.23	+0.20	0.20		0.61	-15.82	1.18
3	8685	350	-15.54	0.05	+0.20	0.20		0.87	-14.47	1.00
4@	8364	310	-15.63	0.19	+0.20	0.20		1.29	-14.14	1.14
5@	8240	400	-15.19	0.44	+0.20	0.20		1.60	-13.39	1.39
6@	8216	362	-15.73	0.19	+0.20	0.20		1.22	-14.31	1.14
7	7995	160	-11.24	0.08	+0.20	0.20		0.08	-10.96	1.03
8	7875	170	0.57	0.05	-0.40	0.20	-0.3		-0.13	0.75
9	7750	200	-0.41	0.03	+0.60	0.30	-0.5		-0.31	0.83
10	7150	160	1.81	0.02	-0.60	0.20	-0.3	0.04	0.95	0.72
11	6790	200	2.29	0.02	-0.80	0.25	-0.3		1.19	0.77
12	6590	288	3.55	0.15	-0.60	0.20	-0.5		2.45	0.85
13	5865	230	3.91	0.15	-1.10	0.25	-0.5		2.41	0.90
14	5660	110	3.63	0.01	-0.60	0.20	-0.3		2.73	0.71
15	5435	210	3.72	0.02	-0.60	0.20	-0.3		2.72	0.72
16	5430	100	3.84	0.02	-0.80	0.30	-0.3	0.06	2.80	0.82
17	5277	120	4.77	0.30	-0.80	0.30	-0.7		3.27	1.10
18	5130	130	3.93	0.02	-0.60	0.20	-0.3	0.09	3.12	0.72
19	5015	200	4.98	0.02	-1.10	0.25	-0.4		3.48	0.77
20	4980	110	4.13	0.04	+0.20	0.20	-0.3	0.16	4.49	0.74
21	4830	240	4.81	0.03	-0.60	0.20	+0.2		4.41	0.73
22	4710	150	4.57	0.01	-0.60	0.20	-0.3		3.67	0.71
23	4616	224	5.18	0.30	-0.60	0.20	-0.5		4.08	1.00
24	4190	300	4.49	0.02	-0.30	0.25	0.0		4.19	0.77
25	3945	150	4.43	0.03	+0.20	0.20	-0.3		4.33	0.73
26	3600	200	6.19	0.02	-1.10	0.30	+0.1		5.19	0.82
27	3370	240	6.23	0.02	-1.10	0.30	+0.1		5.23	0.82
28	1545	70	5.65	0.02	-1.10	0.30	-0.4		4.55	0.82

* Two sigma deviation in radiocarbon age is given to each date.

@ Dates of upper stratigraphic contacts. 8364±310 stems from 9195±155 (Birm.139). 8240±400 stems from 8925±200 (Birm.140). 8216±362 stems from 8330±125 (Hv.3462).

$ A is the indicative meanings of sample types (woody fen, reedswamp, saltmarsh and gyttja) to tidal level of MHWST.

B is the variation of MHWST marks at different locations around Morecambe Bay relative to the MHWST mark at Heysham.

C is the estimated compaction value of organic deposits.

The final error term is calculated by adding up the sampling error, range of indicative meaning and the operational error.

5.4. Reconstruction of Flandrian Sea-level Changes

This section is composed of three sub-sections: direction of Flandrian sea-level movements, rate of Flandrian relative sea-level changes, and local and regional crustal movement.

5.4.1. Direction of Flandrian sea-level movements

As the described in the last section, there are 28 sea-level index points available for the reconstruction of the Flandrian sea-level history in Morecambe Bay. In order to realise this goal, an inductive model is employed. This model was introduced by Shennan et al. (1983). It expresses a currently acceptable concept that sea-level index points could be statistically analyzed and applied to produce the tendencies of sea-level movement.

The corrected sea-level index points, each with two standard deviations of their radiocarbon ages and a range in altitude, are listed in Table 5.3. Of these, thirteen are transgressive overlaps and the other fifteen are regressive overlaps. Ten regressive overlaps are related to a slowly rising sea-level.

Shennan et al. (1983, p405) argued that "an individual sea-level index point is unlikely to show unequivocally a regionally significant process such as a rise or fall in sea-level. By comparing all available lines of evidence, ... the processes operating on a wider scale may be interpreted in terms of the dominant tendency of sea-level movement. ...... A positive tendency of sea-level movement is defined as an apparent increase in the marine influence and a negative tendency of sea-level movement is the apparent decrease of the marine influence." Following these ideas, Shennan et al. (1983) introduced a statistical method and used a histogram to establish the tendencies of sea-level movement in the Fenland and northwest England. Here, applying Shennan et al.'s method, the sea-level index points from Morecambe Bay are subjected to histogram analysis.

At first, from the distribution of the index points, combined frequency histograms occurring within a certain 50-yr interval taken from Table 5.3. (two standard deviations are assigned to each radiocarbon date) are graphed in Figure 5.2. Second, the fifteen regressive overlaps are classified into two groups: one relative to a falling sea-level (those with R mark in Table 5.1.) and another relative to a slowly rising sea-level (those with Ra mark in Table 5.1.). these two groups of regressive overlaps are plotted in Figure 5.3. as combined frequency histograms. In Figure 5.3., the overlaps in group R are gained negative values whilst those in group Ra are gained positive values. Third, all transgressive overlaps and regressive overlaps in group Ra are plotted together with positive values in Figure 5.4. Whilst regressive overlaps in group R are plotted in Figure 5.4. with negative values. The chronological histograms in Figure 5.4. are used as the basis for the chronological division of positive and negative tendencies of sea-level movement. Therefore, boundaries for each positive/negative tendency period are estimated and drawn in Figure 5.5.

From the histogram analysis, six periods of positive tendencies and four periods of negative tendencies of sea-level movement in the Flandrian are identified. The periods of positive tendencies are: 9500-7000 (P1), 6700-6200 (P2), 5750-4700 (P3), 4100-3500 (P4) and 1650-1500 (P5) B.P. The periods of negative tendencies are 7000-6700 (N1), 6200-5750 (N2), 4700-4100 (N3) and 3500-3200 (N4) B.P.

5.4.2. Rate of Flandrian relative sea-level changes

The corrected sea-level index points from Morecambe Bay are plotted in a time/altitude graph (Fig. 5.6.), in which an error box is given to each index point. The error box is regarded as two standard deviations of their radiocarbon ages and the altitudinal variation as indicated in Table 5.3. Second, a narrow band about ± 1m is drawn to outline the error boxes. Third, an estimated curve within the band and through selected index points is constructed. Some index points were unselected because of their qualities compared with others. For example, the date 6790 ± 200 was collected from a small hollow within Roudsea Wood, in which herbaceous and woody sediments were abundant (Birks, 1982), so that this regressive overlap might form before sea level actually fell.

The narrow band provides an acceptable summary for the sea-level history of Morecambe Bay, while the sea-level curve suggests details of the fluctuation in Fladrian sea-level. The sea-level curve is used to calculate the rates of relative sea-level change. The calculation is based on the spacial variation of the relative sea-level curve in a 100-year interval. On comparison of the sea-level curve (Fig. 5.6.) with the sea-level tendency model (Fig. 5.5.), the history of Flandrian relative sea-level in Morecambe Bay is summarised and divided into three main periods. These three periods of sea-level history are described as follows.

Period One (RR)

This is a period of rapid rising sea-level from about 9500 to 7000 B.P. relating to tendency period P1 (Fig. 5.7.). This period of rapid rising sea-level has resulted in sedimentary depositions in Morecambe Bay of Unit II - Major Marine Sequence as suggested in Section 4.7. This period comprises four sub-periods. **RR1**: from 9500 to about 8750 B.P., sea level rose rapidly. At the end of this sub-period, sea water was able to inundate the Bay at an altitude of -17.0 m O.D. (MHWST). **RR2** (8750-8100 B.P.): the rising sea-level slowed down and the rate was around 2.5 mm/yr, allowing extensive saltmarsh deposition along the tidal channels, the Kent and the Leven in particular. **RR3** (8100-7800 B.P.): sea level rose rapidly and the rate should exceed 30 mm/yr but could not be quantified yet. At the end of this period, the rising rate of sea level was reduced to around 10.0 mm/yr by 7800 B.P. **RR4** (7800-7000 B.P.): from 7800 to 7000 B.P., sea level rose continuously and fluctuated. First, the rate of the rising sea level reduced from 10.0 mm/yr to 2.0 mm/yr, allowing the lowest organic layer at Skelwith Pool to lie down. Second, sea level rose faster and the rate increased up to 3.5 mm/yr during 7700-7400 B.P. Third, the rate was reduced to 1.5 mm/yr in 7200-7000 B.P. when the second lowest organic layer at Skelwith Pool deposited.

Period Two (FR)

This period is characterised by a fluctuating rising sea-level from 7000 to 4700 B.P. and coincided with tendency periods N1, P2, N2 and P3 (Fig. 5.7.). This period of sea-level changes has resulted in the deposition of Unit III - Secondary Marine Sequence in Morecambe Bay (see section 4.7.). This period includes three sub-periods. In **FR1**, the rising rate of sea level increased from 1.5 mm/yr up to 5.5 mm/yr by 6700 B.P. However, the trend of the sea-level curve in this sub-period is not agreed with the suggestion of the tendency period N1 (Fig. 5.7.). This disagreement arises from the uncertainty of the regressive overlap 6790$\pm$200 which might form earlier than sea level actually fell. In other words, the negative tendency N1 might exist. In **FR2**, sea level kept rising but the rate was reduced to 0.5 mm/yr from 6700 to 6200 B.P., followed by a slight falling in sea level at a rate of about -0.5 mm/yr during 6200-5750 B.P. This sub-period of sea-level movement is also indicated by the tendencies P2 and N2. In **FR3**, from 5750 to 4700 B.P., sea level rose and fluctuated as suggested by the positive tendency P3. The rate of sea-level movement increased to 4.0 mm/yr around 5700 B.P., descended to 2.5 mm/yr around 5500 B.P., then increased again up to at 4.0 mm/yr around 5300 B.P. Around 5150 B.P., the rate of sea-level movements was close to 0 mm/yr. Afterwards, sea level rose again and the rate increased up to 7.0 mm/yr around 5000 B.P.

Period Three (SF)

This period covers the last 4700 years, relating to the Unit IV - Marine Regressive Sequence. The amplitude of sea-level fluctuations has been smaller and smaller during this period. Due to lack of data and information, only two sub-periods are identified and the third one is unclear. In **SF1**, from 4700 to 4100 B.P., sea level fell as suggested by the negative tendency N3. The rate of the falling sea-level was about -1.0 mm/yr around 4500-4400 B.P. In **SF2**, from 4100 to 3500 B.P., sea level rose as indicated by the positive tendency P4, but the rising rate was only about 2.0 mm/yr. This was followed by a fall in sea level during 3500-3200 B.P. as suggested by the negative tendency N4. In **SF3**, evidence of sea-level movements are very sparse. Only a short period of rising sea-level from 1650 to 1500 B.P. is indicated.

The sea-level curve is broken at a period between 7990 and 7800 B.P. This is because the two groups of index points have been influenced by processes of crustal movement of different magnitudes. Detail discussion about this point is carried out in the following section.

5.4.3. Local and regional crustal movements

In order to estimate the amplitude of local and regional factors of crustal movement, the regional eustatic curve proposed by Mörner (1984) is used. The corrected sea-level index points are plotted on a time/altitude graph, superimposed by Mörner's curve (Fig. 5.8A.). Subtracting the eustatic value, the residuals of the sea-level index points (Fig. 5.8B.) provide an estimate of crustal uplift/subsidence (including glacio-isostatic, hydro-isostatic and tectonic components) and the possible changes in tidal range.

In Fig. 5.8B., there is a clear distinction between the index points younger than 7800 B.P. and those older than 7800 B.P. These two groups of residuals do not fall into a single linear or curvilinear line. The residuals of the younger group reveal an exponential decline in uplift at a curvilinear form which is very similar to those from Solway Firth (Fig. 8B.) and northeast Scotland (Shennan, 1989). The older group of residuals comes from the basal peat samples and shows about 8 to 10 m dropping down from the curvilinear line constructed by the younger group of residuals.

General speaking, the uplift pattern in Morecambe Bay during Flandrian is similar to that in Solway Firth (Fig. 5.8B.). The altitudinal difference between these two curves in Figure 5.8B. is about 4 m at 7000 B.P., about 2.8 m at 6000 B.P. and about 2.5 at 4000 B.P. Comparing with the uplift curve in the western Forth Valley suggested by Sissons and Brooks (1971), the altitudinal difference between Morecambe Bay and Forth Valley is about 5 m at 4000 B.P. In fact, the distance between Morecambe Bay and Solway Firth is about 52 km which is nearly half of the distance from Morecambe Bay to the Forth Valley. The relationship between amplitude of uplift and distance from the glacial centre at Forth Valley is listed in Table 5.4. and plotted in Figure 5.9.

It seems that the sea-level data from Morecambe Bay fit very well with the uplift pattern in the northern Great Britain suggested by Shennan (Figure 9, 1989).

Table 5.4. Relationship between uplift and distance

	Distance (km)	Uplift (m) 4000 B.P.	Uplift (m) 7000 B.P.
Forth Valley	0	6.5	18.6
Solway Firth	68	3.1	10.0
Morecambe Bay	120	0.6	5.7
S. Lancaster	155	0.0	4.8

Attention should also be drawn to the seven index points which are derived from the basal peat unit at lower Leven estuary and Heysham Harbour and drop down about 8 to 10 m from the residual curve (Fig. 5.8B.). It must be stressed that those index points fitting with the residual curve are younger than 7800 B.P. and come from onshore sites on the Leven and Kent estuaries in particular. The altitudinal difference between the two groups of residuals may come from several causes. First, the altitudinal difference may partly be a result of the error of the sea-level index points and the eustatic curve itself (Mörner, 1984) in age and in altitude. It was indicated (Shennan, 1989) that, for the period 7000-8500 B.P. when sea level was rapidly rising, any small shift in the age will result in a relatively large change in the estimation of vertical displacement. In general, therefore, the altitudinal error of the sea-level index points will meet a difference of ±2m. For this particular period (7000-8500 B.P.), an error band of the eustatic curve should also be as large as the similar value, ±2m.

Second, apart from the errors of sea-level data, the remaining difference between the two groups of residuals is still great, approximately within a range of 6m. This range of altitudinal difference was also indicated by Flemming (1982), when he computed the model of eustatic change in the U.K. Such difference in altitude was explained as a result of a rapid subsidence in Morecambe Bay during the 8th-9th millennium B.P. (Flemming, 1982). This assumption is supported by Figure 5.10. which shows the elevation of sea-level index points from the northern part of Morecambe Bay to Lytham and Nancy's Bay, southwest Lancashire (Tooley, 1978a). This figure suggests a subsidence in the central and southern parts of Morecambe Bay and an uplift in the north shore of the Bay. Such uplift in the north shore and subsidence in the central and southern parts of the Bay suggest a local glacial-isostatic tilting derived possibly partly from the deglaciation of the local ice cap over the mountains in the Lake District. It is indicated that the local ice cap in the Lake District has disappeared by before 14,500 B.P. (Pennington, 1978), and that the episodes of small glacial readvance ended by 10,250 B.P. (Huddart et al., 1977; Knight, 1977; Lamb, 1977; Goudie, 1977; Tooley, 1987b). The effect of the local glacio-isostatic movement derived by the Lake District ice cap might have ended a few thousands years ago. In other words, this local glacial-isostatic movement may have affected those sea-level index points which are older than 4000 years (Fig. 5.10.).

Third, accompanied with the rapidly rise in sea level in the early Flandrian, a rapid loading of sea water and clastic sediment in the Bay could also have enhanced the subsidence of the Bay, particularly its southern part. Applying Newman et al.'s formula (1980), the central and southern parts of Morecambe Bay might have subsided 8.9 m by sediment loading. It must be noted out, however, that this sort of subsidence depends not only the loading and densities of sediment and mantle materials but also on the crustal flexural parameter (Andrews, 1970). Therefore, the actual subsidence caused by the sediment loading must be much less than 8.9 m, due to the fact that Morecambe Bay is only a small basin of about 15 km in diameter.

Fourth, changes in palaeo-tidal range may have played an important role for the altitudinal difference between the two groups of residuals. In fact, tidal range has changed through time along some coasts (Kidson and Heyworth, 1979; Scott and Greenburg, 1983; Tooley, 1985a; Roep and Beets, 1988; Woodworth et al., 1991). In Table 5.3. and Figure 5.6., the height of MHWST as the index points represented was assumed as the same as the present one and unchange throughout the Flandrian. It is assumed that the tidal range might be lower than the present one when the basal peat was laid down about 7990-9270 B.P. Whilst, following the rapid rising sea-level around 7800 onwards, the tidal range might be higher than the present one. As a result of the changes in paleao-tidal range, the altitudinal difference of two residual groups would be enlarged. The mechanism causing the changes in paleao-tidal range is explained as follows. In Morecambe Bay, it seems that, during the 8th-9th millennium B.P., sea water in the Bay was very shallow. Meanwhile, the sea-bed was relatively flat due to the infill of the post-glacial alluvial and lacustrine deposits (Fig. 4.2.). As a result, the geometric boundary of the bay would be largely changed between high and low tides. Therefore, the tidal range was lower than the present one. Contrast, during the early 7th millennium with a rapid rise in sea level, sea water was much deeper and the geometric boundary of the Bay was delimited by solid rocks. As a result, the high water levels could be considerably enhanced when a tide wave moves into the Bay. The tidal range was therefore higher than the present one.

5.5. Discussion

Attention can be drawn to three major aspects in the present study can be made in the following sections.

5.5.1. Interpretation of sea-level evidence

It is well known that alternating deposition of marine and terrestrial sediments indicate lateral movements of land and sea margins. Although such movements are mainly as a result of the oscillations in sea level, sediment supply may play an important role in some cases. During the Flandrian, for example, sea level rise was accompanied by sedimentation on a comparable scale (Kidson, 1982). Kidson and Heyworth (1976) suggested that as the rate of sea level rise slowed in the later Holocene, it would variously fall below or exceed the rate of sedimentation. Alternations of marine and terrestrial sediments, particularly when the former are clastic and the latter biogenic, could be emplaced without any falls of sea level. Streif (1978) also suggested that, when fen peat layers occur, as they often do 'in regressive overlap' on top of marine or brackish deposits, it is 'misleading to interpret each regressive overlap as an indicator of a sinking sea level', and concluded that phases with a relatively low rate of sea level rise seem to offer the most favourable conditions for the formation of intercalated peat layers. Therefore, whether or not the reconstruction of sea-level history from such sedimentary evidence is adequate, would fully depend upon the methods of interpretation which are applied to assess the evidence. Nevertheless, Streif's (1978) and Kidson and Heyworth's (1976) suggestions are agreed upon and supported by the present study.

Consequently, the present study suggests that a regressive overlap should be examined carefully and in detail for microfossil analysis, and its implication to changes in sea level should be identified, before it is applied to construct the history of sea level in local and regional scales. In fact, some of the regressive overlaps are associated with a rising water level. Furthermore, in terms of coastal responses to a changing sea-level, this sort of classification for the regressive overlaps would be very important. In order to realize the aims of the present study, an effort has been put to distinguish evidence of a slowly rising sea-level from regressive overlap. Thus, processes of coastal sedimentation responsible for the changes in sea level can be emphasised. In other words, a transgressive overlap is mainly related to a relatively rapid rise in sea level.

5.5.2. Sea-level history in Morecambe Bay

Compared with other coastal sectors of Britain, the history of sea-level changes in Morecambe Bay has similarity and dissimilarity with the others, such as those in southwest Lancashire (Tooley, 1978a, 1982), southwest Scotland and the Solway Firth (Andrews et al., 1973; Jardine, 1975), the Fenland (Shennan, 1986a,b), southeast England and the Thames Estuary (Devoy, 1979, 1982).

In terms of the similarity, for instance, the sea-level curve for the period from 8200 to 3500 B.P. in Morecambe Bay is coincident with the form of sea-level history in the lower Thames (Devoy, 1979). In both areas, a rapid rising sea-level occurred about 8100-7800 B.P., followed by a fluctuating rising sea-level at a reduced rate.

However, there are two major differences between the two areas.

Looking closer at the fluctuations of sea level at first, there are more fluctuations in Morecambe Bay than in the Thames Estuary. Secondly, during the last 3500 years, sea level in Morecambe Bay fell slightly, but still rose in the Thames Estuary. It is clear that these differences are mainly a result of the uplift in Morecambe Bay and the subsidence in the Thames Estuary. Furthermore, archaeological evidence assembled by Evans (1953) suggested that from the mid-twelfth century marine inundations became frequent and the deposition of fine silty-clay saltmarsh sediments commenced and has continued until today. Such continuous relative rise in sea level has allowed about 3.1 m of saltmarsh sediments to accumulate over the Romano-Saxon land-surface near the main channel. In contrast, no similar evidence has been found in Morecambe Bay.

5.5.3. Coastal responses to a changing sea-level

The third important finding of this chapter is the responses of coastal sedimentation to a changing sea-level.

It is indicated that a rapidly rising sea-level during the early 7th millennium may have been accompanied by an enhanced range of tidal regime in Morecambe Bay. Such a rapidly rising sea-level and the high range of tidal regime could encourage intertidal clastic sediments to be deposited in places further upstream. It could also lead to a retreat of biogenic sediments, which could only be deposited at an altitude much higher than the MHWST (compared with the present level). A rapidly rising sea-level could also encourage intertidal clastic sediments to overlie the former organic deposition. Based on the present study, a rising sea-level with a rate over 8-10 mm/yr could cause extensive inundation of sea water all over the coastal lowlands which were lower than the height the sea water reached at that time. This did actually happen at the end of the 8th millennium and during the early 7th millennium in Morecambe Bay.

However, a rising sea-level at a reduced rate could also cause a continuous marine inundation or marine deposition to overlie the former formation. Such sort of situation had occurred as a rising sea-level with a rate of from 4 to 8 mm/yr. As the sea level rises at a rate around 3-4 mm/yr, saltmarshes and reedswamps (Phragmites, in particular) could grow rapidly beyond the MHWST mark and keep pace with the marine clastic deposition on the intertidal flat. In this case, the coastline (i.e. the boundary dividing the intertidal clastic deposits and the supratidal organic deposits) would move very little laterally, except for the side-ways movement of a tidal channel. An example is the Phragmites deposition in Skelwith Pool (Fig. 4.6.). If sea-level fluctuates at a rate of 0-2 mm/yr, saltmarshes and reeds followed by fens, could colonise and be deposited upon the former upper intertidal flats. The coastline could move seaward, except for the side-ways movement of a tidal channel. It is very common in Morecambe Bay during the last three thousand years.

As sea level moved negatively, saltmarshes, reeds and fens would be colonised and deposited further seaward at a rapid rate. The intertidal zone would also move seawards. In onshore sites, saltmarshes and reedswamps would give way to fens and alder carr, or shrub and tree communities, associated with a fall in the ground water table.

In the Fenland, Shennan (1987b) suggested a rise in sea level at a rate over 5 mm/yr could form a transgressive overlap. In Morecambe Bay, Skelwith Pool in particular, the critical rate seems to vary from 3.0 mm/yr (during 7500-7300 B.P.) to 4.0 mm/yr (during 5400-5600 B.P.). Such variation seems to depend strongly on coastal (intertidal) morphology and sediment availability. In other words, the intertidal area in Skelwith Pool was probably shallower during 5400-5600 B.P. than that during 7500-7300 B.P., and so more sediment was available.

CHAPTER VI

RECENT AND FUTURE SEA-LEVEL CHANGES

6.1. Introduction

This chapter serves as an introduction to the chapters which follow. This chapter has therefore four aims: (1) to discuss the uncertainties involved in the sea-level scenarios of the next century estimated by Hoffman (1984) and suggested by the IPCC report (Houghton et al., 1990); (2) to make a judgement for prediction of the projected (global) sea-level rise in the next century; (3) to analyse the local or regional trend in changes of water level measured by tide gauges; and (4) to describe critically sea-level scenarios in the next century for the two areas studied - Morecambe Bay and the Thames Estuary - by considering the local factors affecting the impacts such as their geometries and crustal movements.

The theory of Greenhouse Effects and evidence of the consequence in global warming and sea-level rise in the last century have been described in Chapter II and are not to repeated in this chapter.

It is suggested that sea-level changes at any one locality will be determined by one or more of the complex components which determine relative movement of sea level (Mörner, 1980b; Shennan, 1989; Dugdale, 1990). On a global scale, the major component of sea-level change is termed eustatic (see discussions in Chapter II). In this chapter and those following, sea-level change at the global scale means the global eustatic change. However, for the studies at regional and local scales, such as for the two areas studied, relative sea-level change is suitable to be applied, due to the importance for a locality of the changes of sea-level relative to the land, i.e. whether the land would be inundated by the rising sea-level or not. Factors related to relative sea-level changes include: ocean water volume (eustasy), the geoid, crustal deformation (isostasy and tectonics), coastal morphology and processes, tidal regime and extreme events, and effects from human activities.

For the same reason, during the analysis of secular sea-level changes in the past century, both mean sea-level and annual maxima are applied, due to their implication to the current study. A comparison between mean sea-level and tidal levels (MHWST, HAT and the abnormally high water level) will also be mentioned.

6.2. Sea-level Scenarios for the Next Century

There is little doubt that global warming is able to increase the global eustatic component of relative sea-level rise (Hoffman, 1984; Warrick and

Farmer, 1990). The warming could partially melt the ice sheets over Antarctica (Thomas, 1985b; Bindschadler, 1985) and other small glaciers (Meier, 1984; Warrick and Oerlemans, 1990) and could also result in thermal expansion of sea water (Gornitz et al., 1982; Wigley and Raper, 1987), all of which could consequently raise the global eustatic sea-level. The global sea-level trend for the past century has some similarity of form to the trend in global surface air temperature (Hansen et al., 1981). Most of the positive correlation arises from the general increase in both sea level and temperature (Gornitz et al., 1982).

Hoffman (1984) suggested that future global sea-level would depend primarily on three factors: the total quantity of water filling the oceans' basins; the temperature of the oceans' layers; and the bathymetry of the ocean floor. From this knowledge and considering the emission of the greenhouse gases and the sensitivity of the climate system, Hoffman (1984) presented a range of estimates for sea-level rise, termed scenarios (Table 2.3.), covering the period 1980 to 2100.

Warrick and Oerlemans (1990) suggested a relatively low estimate of sea-level rise (within 8.7 and 28.9 cm) over the period 1985-2030 (Table 2.4.), based on their calculation mainly concerning the contribution of the thermal expansion of sea water and the partial melting of mountain glaciers and of the Greenland ice sheet. Based on the estimation in global warming of 0.5-2.5 °C over the period of 1985-2030, Warrick and Oerlemans (1990) indicated the best estimate of sea-level rise for the period of 1985-2030 is 17-26 cm. In which, the oceanic thermal expansion provides a positive contribution of 52 percent to the rise; glaciers and the Greenland ice sheet produce 49 and 12 percent respectively; the Antarctic ice sheet, however, induces negative contribution of -13 percent to the rise in sea level, due to that an increase in temperature should increase precipitation and accumulation of snow (Warrick and Oerlemans, 1990). However, they quote D.R. MacAyeal that the impact of a greenhouse warming scenario on the West Antarctic ice sheet will increase mass out flow in 100 to 200 years, and that the contribution of West Antarctic to sea-level change would be -10 cm in 100 years (because of increased precipitation leading to surface accumulation), +40 cm in 200 years and +30 cm in 300 years. In other words, the West Antarctic will become an important (positive) contributor to sea-level rise at the end of the next century.

Both estimates are the average values of global eustatic rise and lack consideration on the crustal response to the loading of melting water in the oceans and unloading of ice on land, and on geoidal configuration. Clark and Primus (1987) indicated that the melting or retreat of ice sheets does not result in a uniform rise in observed sea-level everywhere, because the observed sea-level change is actually the difference between two dynamic surfaces ------ the geoid and the earth's solid surface. For instance, they (1987) suggested that Iceland would experience a fall in sea level of 200 cm if 100 cm eustatic sea-level contribution is added to the ocean from melting of the Greenland ice sheet. This fall in sea level occurs because the land there will rise due to glacial unloading on Greenland and the geoid will lower from the reduced ice mass. England would observe no change in sea level but New Zealand would experience a 120 cm rise in sea level. Their estimation presented a percentage change for any particular eustatic contribution, and the change at any locality will be the sum of the contributions from each ice sheet. As an example suppose that by the year 2100 Greenland contributes 25 cm and Antarctica contributes 80 cm to global eustatic rise then the actual rise at London would be 95 cm (25 percent of 22.9 and 80 percent of 111.3) (Dugdale, 1990).

6.3. Uncertainties

Estimating the future global warming induced sea-level rise is a complex task. It is difficult to generate a precise forecast due to the large degree of uncertainty in many of the factors influencing the sea level (Barth and Titus, 1984). Hoffman (1984) suggested that part of the variance between scenarios may be an artifact of the relatively crude methods used for estimating sea-level rise, rather than a lack of insight into its physical mechanisms. In order to improve substantially the estimates of future sea level rise and to narrow the range of scenarios, more time and more scientific research will be needed. However, during this stage of the study, some criticisms can be given to the estimates in order to provide a set of relatively adoptable scenarios for future sea-level rise.

For instance, the major factors influencing sea level that Hoffman (1984) considered are: (a) future atmospheric composition, including CO_2 emissions and concentration of other trace gases; (b) future global temperature, including initial warming and feedback effects, and climate sensitivity; and (c) future ocean responses, with thermal expansion of ocean water, and snow and ice contributions.

At first, the assumptions in Hoffman's scenarios include that the world population will achieve zero growth by 2075, and that energy efficiency will be improved. The World Energy Model (Institute for Energy Analysis, 1981) on which Hoffman's estimates are based provides assumptions that per capita economic growth will decrease from 3.5 percent per year in 1980 to 2.2 percent by 2100 for the high scenario, and diminish from 2.2 percent in 1980 to 1.7 percent in 2100 for the conservative scenario. Obviously, all these rates of economic growth are lower than those experienced in the last thirty years, and seem to under-estimate future growth. At least, the global rate of future economic growth could probably be the same as the past decades, saying 'business as usual' (Wigley, 1989). Most of the CO_2 generated today comes from the Industrialized Countries. However, the Lesser Developed Countries including the former USSR, China and India will become major contributors within the next 30 years. For instance, the commercial energy consumption from 1980 to 1985 decreased by -1 percent in industrialized countries, but increased by +13 percent in the former USSR and eastern european countries and by +22 percent in developing countries (British Petroleum, 1986).

The growth of economic activities seems to be continued for the next decades. CO_2 emissions are therefore unlikely to be curtailed. This is because the cost of using coal, gas, and oil is low compared with nuclear and solar power. This relative cost advantage is expected to continue. Although some of the developed countries have intended to reduce use of fossil fuel in order to curtail CO_2 emissions, the feasibility of instituting such a ban by 2000 or even later is doubtful, because reaching a worldwide consensus on curtailing emissions is extremely difficult. Any individual nation that curtails its own emissions will delay the day when CO_2 concentration doubles by a few years at most (Barth and Titus, 1984).

The fraction of emissions that remains in the atmosphere is poorly known, due to the complex biogeochemical process of carbon cycles which are mainly and largely fluxed among biosphere, oceans and atmosphere. Hoffman (1984) suggested that largely because the upper layers of the ocean would approach saturation as warmer surface temperatures reduced vertical mixing of the oceans, the rate of atmospheric retention of CO_2 would grow from 60-80 percent by 2100. However, neither Hoffman's model nor Warrick and Oerlemans' model consider the deforestation and desertification factors which are likely to reduce the carbon reservoir, that indirectly contribute to the atmospheric CO_2 concentration.

Due to the insufficient knowledge, only four of the other important trace gases (methane, nitrous oxide, and two chlorofluorocarbons) were considered in Hoffman's model. These gases are many times as effective as CO_2 in terms of greenhouse effects and have increased their atmospheric concentration much quicker than CO_2, but they are much less abundant (Hoffman, 1984; Houghton et al., 1990). For the global warming during the last decade, Houghton et al. (1990) suggested that the future contribution of CO_2 was expected to be only about 55 percent, but the CFCs, up to 24 percent, and methane and nitrous oxide, 21 percent. However, for a period over 100 years, in the next century for example, carbon dioxide and methane would be the most important contributors. Their contribution to the global warming were expected (Houghton et al., 1990) to be 61 percent (CO_2) and 15 percent (methane).

Secondly, in a climate system, the analogue of the steadily increasing pedal pressure is the steadily increasing forcing due to greenhouse gas concentration build up (Wigley, 1989). It was indicated (Wigley, 1989) that the time-varying temperature changes are referred to as the transient response. The final temperature level that would be attained for a given forcing level is therefore called the equilibrium response. It was suggested (Wigley, 1989) that the lag between transient and equilibrium responses would depend on a variety of factors: the oceans' effective heat capacity, the rate of change in greenhouse gas concentration, and the climate sensitivity. The climate sensitivity, however, depends critically on a variety of feedback processes which exist within the climate system. From this point of view, Warrick and Farmer (1990) suggested that a climate sensitivity model response to a doubling CO_2 may produce a rise in temperature of 1.5-4.5 °C, but the actual warming should be only 0.5-2.5 °C. But, a rise in temperature of 1.5-4.5 °C is still likely, according to the National Academy of Sciences' estimated range of the impact of a CO_2 doubling on average surface temperature (Hoffman, 1984) and the IPCC report (Houghton et al., 1990).

There are likely to be two important feedbacks which have been concerned , investigated and somewhat understood. Hansen et al. (1984) suggested that the most important feedback will result from the warmer atmosphere's ability to retain more moisture. Because water vapour also absorbs infra-red radiation, additional heating will result, so that doubled CO_2 would increase the atmosphere's water vapour content by 30 percent, heating the earth an additional 1.4 °C. However, the increase of atmospheric moisture would result in more extent of cloud cover. As a consequence, the increased clouds could reflect more sunlight back into space. Therefore, further studies are needed to work out how much infra-red radiation could be absorbed and how much sunlight could be reflected back by the increased atmospheric moisture. Nevertheless, Mitchell (1989) tested a Global Climatic Model with water vapour and cloud feedbacks and gave results in the upper part of the predicted warming range from 1.5 to 4.5 ^{0}C. He further indicated that a 1 ^{0}C increase in atmospheric temperature should be associated with a 6 percent increase in water vapour - this increase in water vapour enhances the greenhouse heating of the troposphere in a positive feedback effect.

Another feedback concerns the impacts of snow and ice cover on the earth's albedo. Ice and snow reflect most of the sun's radiation, while soil absorbs it. An increase in surface temperature would melt snow and ice and thereby allow the earth to absorb energy that would otherwise be reflected back into space. Thus, an additional warming of 0.4 °C is expected (Hansen et al., 1984). However, a global warming could not only melt ice and snow in some places, some mountain glaciers and the Greenland ice sheet in particular, but also cause more precipitation and increase ice accumulation in Antarctica (Warrick and Farmer, 1990).

Most researchers agree that polar temperatures would increase two or three times of the earth's average increase (Barth and Titus, 1984). This regional deviation would also significantly affect the feedback mechanism. For Antarctica in particular, a warming up, as Warrick and Farmer suggested (1990), could cause more precipitation, so that the ice accumulation is increased. Notwithstanding this optimistic conclusion, NASA launched the Sea RISE initiative in 1990 (Bindschadler, 1990) with the goal to predict the contribution of marine ice sheets to rapid changes in global sea-level in the next decades to few centuries. Marine ice sheets are believed to be inherently unstable and prone to rapid collapse. Therefore, a rapid rise of sea level is still likely, due to the marine ice sheets. The West Antarctic ice sheet in particular, is known to be changing rapidly now.

6.4. The Best Guess

At present, Hoffman's model (1984) and the IPCC report (Warrick and Oerlemans, 1990) are the two outstanding predictions of global sea-level rise of the next century. Main difference between these two predictions arise from their assessment to the contribution of the Antarctic ice sheet.

The IPCC report presents a prediction to the year 2100. Even if the greenhouse forcing of Business-as-Usual Scenario was stabilised in A.D. 2030, Warrick and Oerlemans (1990) stress the substantial commitment of sea-level rise after A.D. 2030 as a consequence of lag effects arising from the thermal inertia of the oceans and a response, continuing beyond A.D. 2030, of land ice to climate change.

In Hoffman's model, it is assumed that for the conservative and mid-range low scenarios, the rise in sea level from deglaciation would equal the contribution from thermal expansion, giving a figure of 56.2 cm and 144.4 cm; while for the mid-range high and high scenarios, it would be twice the contribution, with a value of 216.6 cm and 345.0 cm. It means that the deglaciation factor in Hoffman's model only contributes a rise in sea level of

28.1-72.2 cm for the conservative and mid-range low scenarios, and 72.2-115.0 cm for the mid-range high and high scenarios.

The judgement of this thesis is that a rise in sea level during the next century is likely with values higher than the Business-as-Usual Scenario that the IPCC report suggested, and may reach the mid-range estimates that Hoffman suggested, according to the following reasons:

> (A) Mercer (1978) has suggested the potential of the West Antarctic ice sheet, its link to the greenhouse effect, consequential catastrophic melting and a rise of sea level of 5 metres. Reference has been made by Tooley (1978a) to this potential, and a comparison made with the catastrophic melting of the Laurentide ice sheet 8000 years ago. The present sea-level study in Morecambe Bay (Chapter V) also indicates variable rates of sea-level rise during the Flandrian.
>
> (B) Although there are large uncertainties involved in the Hoffman's model, the available knowledge is sufficient to estimate the likely range of sea-level rise in the next century. For the high scenario in Hoffman's model, when looking at the geological evidence associated with sea-level changes in the past ten thousands years, it is interesting to note that at the maximum of the last ice age, 18,000 years ago, the world was only about 4-5 °C colder than today, and since then sea level has risen over 121 metres (Fairbanks, 1989).
>
> (C) Greenhouse forcing is still increased, at least during the next few decades. A warming in atmospheric temperature is likely to reach the upper part of the predicted range of 1.5 - 4.5 ^{0}C during the second half of the next century.
>
> (D) A 1 ^{0}C increase in atmospheric temperature should be associated with a 6 percent increase in water vapour --- this increase in water vapour could enhance the greenhouse heating (Mitchell, 1989).
>
> (E) The West Antarctic ice sheet will possibly become a

> positive contributor to the rise of sea level before the end of the next century, and the mass out flow will rapidly increase. However, catastrophic discharge of meltwater is more likely to lead to a rapid rise in sea level.

Therefore, two scenarios, Scenario 1 and Scenario 2 (Fig. 6.1.), are applied during the studies in this and following Chapters. The Scenario 2 is borrowed from the mean value of the mid-range low and high estimates in Hoffman's prediction (1984). The Scenario 1 is employed from the best guess of Business-as-Usual Scenario in the IPCC report (Warrick and Oerlemans, 1990). These two sea-level scenarios are listed in Table 6.1., in which the rates of sea-level rise are recalculated in 50-year average in order to make them comparable to the rates of sea-level change in the Flandrian.

In the Hoffman's Mid-range low estimate (1984), 1/2 of the rise in sea level stems from deglaciation, but 2/3 of the Mid-range high estimate comes from deglaciation. It seems that, in the Scenario 2 (Table 6.1., an average of the Mid-range estimates of Hoffman's prediction), there is at least 1/2 of sea-level rise related to melting of Greenland and Antarctic ice sheets and other small glaciers. As Clark and Primus suggested (1987), the local sea-level rise in the Thames Estuary would be 95 cm, if Greenland contributes 25 cm and Antarctica contributes 80 cm to the global eustatic rise by the year 2100. In the present study, therefore, the figures of the Scenario 2 in Table 6.1. have been reduced by the value of the changes in geoid for the two areas studied. It is for example assumed that about 1/3 of the rise in sea level is caused by the melting of Greenland and Antarctic ice sheets. Then, only 95 percent of this rise (i.e. 1/3 of the total rise) should be considered.

Table 6.1. Sea-level rise scenarios adopted
(from Hoffman, 1984; Warrick and Oerlemans, 1990)

A. Rates of sea-level rise in mm/yr (50 yr mean)

Years	Pre-2000	2000-2050	2050-2100
Scenario 1	4.6	5.4	7.0
Scenario 2	6.5	11.7	24.6
Scenario 2*	6.0	10.4	22.2

B. Magnitudes of sea-level rise in metre (starting from 1990)

Year	2000	2025	2050	2075	2100
Scenario 1	0.04	0.16	0.31	0.48	0.66
Scenario 2	0.06	0.33	0.65	1.14	1.81
Scenario 2*	0.06	0.27	0.58	1.05	1.69

* Factor of changes in geoidal configuration is considered

As a result of a time-lag in response to global warming induced by the acceleration in greenhouse gas forcing from 1990 to 2050, the induced sea-level rise in this period is likely close to the Scenario 1. However, due to that the later 50 years in the next century seem to be characterized by the inertia of global warming, a more rapidly rising in sea level, reaching a rate of the Scenario 2, may be likely. This conclusion forms the background of the studies in this and following Chapters.

Three other predictions for future sea-level change are also plotted in

Figure 6.1. for comparison. The Scenario 1 seems close to van de Veen's prediction (1988), and the Scenario 2 is more or less the same as the UK Department of Environment's assumption (1988). Both Scenarios 1 and 2 are close to the NRC's prediction (1987).

CHAPTER VII

COASTAL RESPONSE TO THE CHANGING SEA-LEVEL

7.1. Theoretical Model of Impacts of a Rising Sea-level

In this section, a theoretical model of the likely impacts of a rising sea-level is introduced. This model is constructed on the base of geological evidence and knowledge of contemporary coastal marine hydrology and sedimentology (Fig. 7.1.). The past evidence provide significant clues revealing the consequences of changing sea-level in such confined areas - Morecambe Bay and the Thames Estuary. Applying knowledge of these changes as well as principles of contemporary coastal hydrology and sedimentology, a trend of the natural impacts of a rising sea-level on the two areas in the next century is identified, although quantifying the impacts requires further detailed measurement and modelling. The following discussions fall into three categories: (1) marine hydrological response, (2) intertidal sedimentation, and (3) coastlines and saltmarshes.

7.1.1. The past evidence

It was described in Chapter V that changes in sea level during the Flandrian have greatly altered the physical environment and coastline around Morecambe Bay. A rapid rise in sea level around 8000-7800 B.P. was possibly associated with a strong tidal regime occupying the Bay. Such a rapid rise in sea level resulted in saltmarshes and reedswamps growing further upstream (in the Rusland Valley for example). This was followed by a dominant marine clastic sedimentation in the Bay, particularly in the Leven and Kent estuaries, with a great thickness overlying the Basal Peat. It is assumed that the tidal range was enhanced at the head of the Bay as sea level rapidly rose. During the period of 7800-3500 BP, sea level fluctuated at a rate ranging from -2.0 to +8.0 mm/yr causing dominantly marine deposition to be continued within the estuaries. This allowed alternating organic and clastic materials to be deposited along the landward margin of the Bay. The tidal range in this period was gradually reduced in the estuaries due to the estuaries being gradually silted up and the rise in sea level slowing down. In the last 3500 years, a slightly fluctuating sea-level has led the marine clastic sediments to fill up the estuaries and the Bay. This consequently allowed successively saltmarshes, reedswamps, carrs and raised bogs (mosses) colonising upon the former intertidal flats around the margin of the Bay. At the present day, most parts of the Bay are silted up and the intertidal zone (about 303 km^2) is exposed during low spring tides, except for some tidal channels.

Although the Thames Estuary experienced possibly the same eustatic sea-level history as Morecambe Bay did, the coastal processes in the Thames Estuary during the Flandrian were different. Marine transgressive deposition has dominated the Thames Estuary during the period from 8500 B.P. to 1750 B.P. except for three major regressive phases (Devoy, 1979). Furthermore, archaeological evidence (Evans, 1953) suggested that the last marine inundation of the lower Thames plain took place around the 11th and 12th centuries.

7.1.2. Impacts on coastal hydrology

A recent study of tidal data from 13 stations around the British Isles (Woodworth et al., 1991) indicated that mean tidal range cannot in general be considered as a constant quantity over timescales of several decades or a century but varies at rates between -1.8 and 1.3 mm/year depending on location. The trends of mean tidal range are usually large enough that they should be included in geographical studies of impacts of sea level change. The result also suggested that the amplitude of the nodal signal in MTR records varies from 3.5 percent of epoch 1950 MTR at Lerwick, dropping to approximately 2.7 percent along most of the east and south coasts of Britain, to approximately 2.0 percent in the Bristol Channel, Wales and Isle of Man, and to approximately 2.6 percent in the N.W. England and Ireland. It is interesting to note that the changes in tidal amplitude in most stations show their positive relationship to the trend of mean sea level (Woodworth et al., 1991).

This evidence is supported by geological data. For example, Grant (1970) argued that tidal amplification was non-linear, and suggested that the increase in tidal range in the Bay of Fundy (Canada) began about 6000 years B.P. but most of the increase occurred during the last 4-5000 radiocarbon years, which was controlled by water depth. Using a numerical tidal model and some new empirical data, however, Scott and Greenberg (1983) revealed that tidal amplitude in the Bay of Fundy increased more rapidly during the period 7000-4000 B.P. than in the period 4000-0 B.P. They concluded that changes in water depth within the Bay of Fundy produced little effect on tidal amplitudes in the Bay, but changes in water depth on George's Bank, south of the Gulf of Maine, accounted for all the change in amplitude. Also employing numerical models, Mr. M.J. Davis (in Tooley, 1985b) suggested that in Liverpool Bay the amplitude of the M2 tide was reduced from c. 2.8 m to c. 1.8 m when sea level was lowered by 20 m. He also indicated that at the head of the Bristol Channel the reduction was from c. 4.3 m to c. 1.5 m, but at the mouth of the channel there was a slight increase in amplitude from c. 2.2 m to c. 2.3 m over the same time period. The current study on Flandrian sea-level changes in Morecambe Bay (see Chapter V) suggested that a rapid rising in sea level in the Leven Estuary during the period 7800-8300 B.P. might have induced the tidal amplitude which was possibly higher than the present, and that although sea level continued to rise slightly, the amplitude was gradually reduced since 7000 B.P. because of the silting up of the estuary. Summarising the above studies, it is therefore suggested that changes in tidal amplitude are likely determined by a combination of several factors: not only water depth, but also the geometry, sea-bed morphology, and sedimentation of the location concerned, as well as changes in water depth in adjacent areas such as the eastern part of the Irish Sea.

Theoretically from a hydrological point of view, the tidal range or amplitude in an open sea could be magnified when a tidal wave travels into shallow water (Pethick, 1984), so that a deepening in water depth could reduce the amplitude of the tidal wave. Within a bay or an estuary, however, the process of a tidal wave is more complex than this. For instance, Pethick (1984) expressed the view that, as a tidal wave moves up-estuary, frictional effects cause the wave's energy to be dissipated and the wave height therefore decreases, since wave energy is proportional to wave height. On the other hand, Dyer (1986) suggested that the convergence of an estuary and the reflection of tidal wave energy from the sides and head of the estuary could cause an increase of tidal range towards the estuary head, but the bottom friction could dissipate the tidal energy. He further indicated that tidal range becomes reduced where the elevation of the estuary bed rises above the general low tide level. In the Severn Estuary, for example, the diminution of tidal range does not occur until 15 km from Sharpness when the sea bed rises to low tide level (Dyer, 1986).

The whole process of a propagating tidal wave therefore seems to be that when a tidal wave travels from deep water into shallow water such as the outer part of a bay or the lower reaches of an estuary, the amplitude of the tidal wave could be enhanced. Afterwards when the tidal wave crosses the low-tide dried-out line and continues to travel further up towards the head of the bay or estuary, the amplitude of the wave could be reduced due to the effects of bottom friction. In Morecambe Bay, at present, the dried-out line in low tides (i.e. the line of MLW) lies approximately along a zigzag line from Morecambe to Barrow (Fig. 7.2.). Flather and Heaps (1975) indicated that the amplitude of a M2 tide is increased from the Irish Sea to the area around Heysham, and subsequently decreased in the channels of the Kent and Leven estuaries. In the Thames Estuary, the instrumental records from tide gauges (Bowen, 1972) suggest that the point of maximum amplitude in tidal range occurs at London Bridge at present, providing the Thames Barrier is not closed.

7.1.3. Impacts on coastal sedimentation

As a result of the enhancement of tidal levels, the velocity of tidal streams will vary from place to place. Consequently, the residuals of the tidal stream (or non-tide streams) will also be altered either in their velocities or in their distribution. The implications of changes in velocity of tidal streams and in tidal residuals include the distribution, deposition and erosion of the intertidal sediments.

In general, sea-level rise could deepen the sea water, and enhance the current velocity especially during the flood tides, which could consequently carry more fine-grained sediments upstream until the point where the ebb current due to the river flow becomes dominant in transporting sediment (Dyer, 1986). The significant consequence on sedimentation from a rising sea-level is therefore likely to result from the larger volume of tidal current flowing into Morecambe Bay or the Thames Estuary, so that sedimentary transportation and deposition will be more active.

The response of saltmarshes to the changing marine hydrological condition is more sensitive. In general, marsh surfaces accrete through the deposition of fine-grained, suspended sediment when water flow is baffled by marsh vegetation, while erosion of marshes is a slow process of wave erosion at the seaward edge of the marsh or at cutbanks of meandering streams (Kana et al., 1984). A rapidly rising sea-level, however, could either erode the marsh or deposit clastic sediments upon the former vegetational formation (see Chapter V). A fall in sea level, on the other hand, could allow saltings and marshes to develop seaward upon the intertidal flats. A slowly rising sea-level, however, may not only increase the vertical accretion of saltmarshes but also induce horizontal retreat of saltmarsh cliffs.

Measurements on accretion of saltmarshes have been made in some sites. Richardson (1934) measured the rates of vertical accretion of new saltmarshes in the Dovey Estuary, Wales and found average rates of 7.5 mm/yr in the low marsh and 2.5 mm/yr in the high marsh. Rates of the same order were indicated in the Norfolk marshes by Steers (1960) and Chapman (1974).

Based on more detailed measurements in the Norfolk marshes, east England, Pethick (1981) indicated rates of marsh accretion ranging from 0.02 to 17.0 mm/yr, in which the younger marsh has the greater rate of accretion and vice versa. For example, a 10-year-old marsh has a net accretion rate of 17.0 mm/yr, whilst a 500-year-old marsh, 0.02 mm/yr. A mature marsh, about 200 years old, has a rate of 1.2 mm/yr (Pethick, 1981). A higher rate of saltmarsh accretion was reported by Harper (1979) who examined the accretion rates in detail on the New Marsh at Gibraltar Point, Lincolnshire. Harper (1979) suggested three main zones of marsh development: the upper marsh with steady but slow accretion (less than 10 mm/year), the central marsh with rapid accretion (as high as 50 mm/year), and the lower marsh with erratic fluctuations in level. In the Netherlands, a vertical accretion rate of 10 to 20 mm/yr in man-made foreland marshes was reported (Dijkema et al., 1990).

The variation in rates of marsh accretion seems to depend on wind speed and direction and associated wave activity (Harper, 1979), frequency of inundation (Gray, 1972), availability of clastic sediments and their nature (Hackney and Cleary, 1987; Jacobson, 1988), and the time length of observation and measurement (Pethick, 1981).

7.1.4. The theoretical model

In order to assess the likely impacts in coastal hydrology, sedimentology and coastline in the areas studied due to a rise in sea level, the different processes involved and their interrelations have been analysed. These processes and their parameters, adapted to the scale of the areas studied, are presented in Figure 7.1. Some parameters have been omitted which are considered of no essential importance to the present study (for example, water temperature and evapo-transpiration are not included). It can also be seen from the diagram that the scale at which some processes operate differ between them.

Block 1 in the diagram represents changes in a global scale, i.e. the changes in eustatic sea-level and atmospheric and oceanic circulations as a result of global warming. Due to thermal expansion being an important contributor to the future eustatic sea-level (Warrick and Oerlemans, 1990), changes in atmospheric and oceanic circulation could affect the magnitude of surface sea-water expansion from place to place. In turn, because of water mass distribution involved, geoid irregularities could occur.

Block 2 indicates the regional and local factors which are not related to the global warming. Geological conditions include processes in different scale. Glacio-isostasy has happened in the British Isles since the last glaciation, resulting in an uplift in Scotland and subsidence in southeast England. However, tectonic movements and sediment compaction may act on a local scale. Astronomical tides are a regional phenomenon.

Block 3 suggests the local processes which could occur in Morecambe Bay and the Thames Estuary. These processes as a result of sea-level rise will be assessed in the following sections.

Block 4 includes the likely physical impacts on the coastal lowlands currently protected by sea defences. Chapters VIII and IX will discuss these impacts.

Assessment of these processes requires detailed information about the parameters involved. Data regarding these processes, sedimentation/erosion and sediment transportation in particular, are rather sparse and need to be updated. Nevertheless, based on the availability and reliability of the data describing the existing nature of the areas studied, a trend of the likely changes in marine hydrology, sedimentation and saltmarshes can be identified.

Referring to Figure 7.1., future changes in mean sea-level seem to mainly depend on the changes in eustatic sea-level and the regional geological factors. Two scenarios of mean sea-level for Morecambe Bay and the Thames Estuary have been given in Tables 7.8. and 7.13. , with consideration of the uplifting factor in Morecambe Bay and the subsiding factor in the Thames, and of the geoid effects of an one-metre melting of Greenland and Antarctica on Morecambe Bay and the Thames. Other processes and parameters in Block 3 are discussed in the following sections.

7.2. Morecambe Bay

Here, the present-day processes of marine hydrology, fresh water discharges, intertidal sedimentation, coastline and saltmarshes in Morecambe Bay are assessed, followed by discussions about their likely changes due to the rising sea-level.

7.2.1. Present marine hydrological conditions

In this section, the tidal pattern, streams, ranges and levels in Morecambe Bay as well as fresh water discharges from the four catchments are introduced.

Tidal pattern and streams

Off the coast of Morecambe Bay, the tide is characteristically semi-diurnal. There are two amphidromic points controlling the pattern of the tide; one located north of the North Channel of the Irish Sea, and the other south towards the Southern Entrance of the Irish Sea (Bowden, 1955). High water across the Southern Entrance occurs at about 7.5 hours lunar time, while in the North Channel high water occurs at 11 hours lunar time. In Morecambe Bay, high water occurs at 10.5 hours lunar time.

It is shown (Bowden, 1955) (Figure 7.3.) that the flood tidal streams flow into the Irish Sea from both the southern Entrance and the North Channel, and follow the general directions of the coastlines. The flow southwards, through the North Channel, divides north of the Isle of Man, part continuing southwards and part turning eastward into the eastern part of the Irish Sea off the coast of Cumbria. Similarly, the flow from the Southern Entrance divides south of the Isle of Man, part continuing northwards and the other part turning eastward into the eastern part of the Irish Sea, off the Lancashire coast. The two eastward streams meet in the area off the coast of Walney Island where together they enter Morecambe Bay.

Within Morecambe Bay, an investigation (Phillips, 1968) on sea-bed water movement using Woodhead sea-bed drifters indicates that there are two different patterns of water movement close to the sea-bed. In the outer part of the Bay there is an anti-clockwise movement towards the north-western shores whereas in the inner part movement is northwards and north-eastward towards the head of the Bay.

From Pringle's (neé Phillips)(1987) explanation, it seems that, in most parts of the Bay, the tidal currents run at a speed of 0.9-1.0 ms-1 at spring tides and 0.5-0.6 ms-1 at neap tides, apart from the deep channels, where the tidal currents reach 1.2-1.5 ms-1 at spring tides and 0.6-0.7 ms-1 at neap tides.

Using a tidal model applied to Morecambe Bay, Flather and Heaps (1975) supported the tidal pattern described above. Stephens (1983) refined this work by producing a higher resolution mathematical model in which the drying banks were reproduced in great detail. He confirmed the tidal pattern and stated that in the Leven and Kent channels very strong southward residuals result from the ebb tide lasting between 7 to 8 hours.

Non-tide currents in Morecambe Bay were primarily examined during an investigation using sea-bed drifters and radioactive tracers (Phillips, 1968). The result is illustrated in Section 7.2.2.

Tidal range and levels

In general, the range of the tide within Morecambe Bay is similar to that of the Solway Firth and the Lancashire coasts (Fig. 7.4.), and is higher than on the other coasts around the Irish Sea (Bowden, 1955). At maximum spring tides the range of tide at Heysham is about 10.5 m and at minimum neap tides it is about 3.4 m (Pringle, 1987). The average range of tide is about 6.2 m in the Bay. The average range depends on the ratio of the amplitudes of the S2 and M2 tidal constituents. Some particular tidal levels in Morecambe Bay have been calculated (Table 7.1.) on the basis of the daily measurement of tide gauges (from the Admiralty Tide Tables 1989). Location of these tide gauges are shown in Figure 7.2. with MHW and MLW as indicated on the Ordnance Survey (O.S.) maps. Unfortunately, tide gauges near the estuary heads provide only levels of MHWST, MHWNT and HAT, as a result of the complete draining in these areas during low waters. Thus, the tidal amplitude of these areas means the difference between the height of estuary bed and the high waters.

It is shown in Table 7.1. that the MHWST level increases about 0.6 m from the mouth (Fleetwood) to the head (Arnside) of the Bay, and the MHWNT increases only 0.3 m over the same distance. These increases may be a result of tidal asymmetry towards the estuary heads. Tidal amplitude increases from the entrance of the Bay to the area near Morecambe (Table 7.1.), but no figure is given to the northern part of the Bay which is exposed during low water. The increase in tidal amplitude when a tidal wave move from the open sea, through the mouth of the Bay, onwards into the central part of the Bay is a normal response to the shallowing of the Bay. When a tidal wave moves into the northern part of the Bay, tidal current not only runs upstream but also spreads upon the vast sand banks along both sides of the tidal channels. As a result of the increasing bottom friction and the reducing energy of the tide wave, the tidal amplitude is reduced and the tidal wave becomes greatly asymmetric. Flather and Heaps (1975) established a numerical finite-difference technique for computing tides in shallowing water and used it to calculate the M2 tide in

Morecambe Bay. They noted that the increase in amplitude of tide from the open boundary, located outside of the Bay in the eastern part of the Irish Sea, to the area around Heysham and the subsequent decrease, was probably associated with the transfer of energy from M2 to its harmonics, in the shallowing channels of the Kent and Leven estuaries.

The values of Highest Astronomical Tide (HAT in Table 7.1.) are calculated based on the HAT of Liverpool, standard port in the Admiralty Tide Tables. These interpolated values become open to errors due to the distortion of the tidal wave and distance from the standard port.

Abnormally high water levels

Height and frequency of abnormally high water levels in Heysham for the past 50 years have been analysed by Lennon (1963) and Graff (1981).

Lennon (1963) investigated the frequency of abnormally high tidal levels in the west coast ports of the British Isles, based on a data set of 14 years for Heysham and 27 years for Fleetwood. His results of the frequency of high water levels are shown in Table 7.2. On the basis of Table 7.2., calculations can be carried out to estimate the likely return periods of abnormally high water levels shown in Table 7.3.

Lennon's work which was based on records between the 1940s and 1950s suggests that a high tide is likely to reach +6.40 m O.D. once in 200 years at Heysham. However, according to the data measured during post 1970s, the level of +6.60 m O.D. has been reached on two occasions, in 1977 and 1983.

An even higher level of +7.60 m O.D. was reached in 1896 during a storm surge (Gray, 1972). A data set recorded for a longer period could therefore suggest that the return period of a certain high tidal level could be shorter than Lennon's estimation. It is implied that in the near future the return period of a certain high level may be much shorter, if the rise in sea level is realised, or the high tidal level in a certain return period will increase remarkably (Rossiter, 1962b). This suggestion is confirmed by Graff's study (Graff, 1981).

Graff (1981) analysed the frequency distributions of annual sea-level maxima at ports around Great Britain and indicated a range of estimates associated with the 1/100 year frequency level for Heysham, which is 6.22-6.82 m O.D. with an average of 6.55 m O.D. (Table 7.4.). Supporting Graff's result, this height have been reached in Heysham for the past 50 years on at least one occasion and over 6.00 m O.D., on 15 occasions. This level is 1.5 m higher than the MHWST in Heysham and can flood most of the coastal lowlands around Morecambe Bay if there are any failure in protection (see Chapter VIII) .

Fresh water discharge

In addition, the fresh water discharges, from the Kent and Wyre catchments into the Bay, are small by comparison, so that their effects to the marine hydrological condition are minimised. However, the River Lune and the River Leven produce relatively large amount of discharges of fresh water into

Table 7.1. Tidal levels in Morecambe Bay (m O.D.)
(data from the Admiralty Tide Tables 1989)

Tide gauge	HAT	MHWST	MHWNT	MLWNT	MLWST	MTL
Barrow	5.41	4.35	2.35	-1.95	-3.75	0.21
Haws Point	5.60	4.50	2.40	-1.90	-3.70	0.19
Ulverston	5.72	4.60	2.60	(dried out in LW)		
Arnside	6.10	4.90	2.70	(dried out in LW)		
Morecambe	5.70	4.60	2.50	-2.00	-3.80	0.33
Heysham	5.60	4.50	2.50	-2.00	-3.80	0.30
Lancaster	6.06	4.85	3.05	(dried out in LW)		
Glasson Dock	5.75	4.60	2.40	(dried out in LW)		
Wyre Lighthouse	5.30	4.30	2.40	(dried out in LW)		
Fleetwood	5.30	4.30	2.40	-1.90	-3.70	0.08

Table 7.2. Frequency of abnormally high water levels.
(after Lennon 1963)

Heysham N=14.1 years			Fleetwood N=27 years		
H	n	n/H	H	n	n/H
4.73	1552	109.80	4.79	1497	55.40
4.88	1132	80.00	4.94	926	34.30
5.03	791	55.90	5.09	550	20.40
5.18	504	35.60	5.24	287	10.60
5.34	329	23.30	5.40	134	4.96
5.49	172	12.20	5.55	54	2.00
5.64	79	5.59	5.70	22	0.82
5.79	26	1.84	5.85	8	0.29
5.95	5	0.35	6.01	0	0.00
6.10	1	0.07			
6.25	0	0.00			

H = Height in metres above O.D.
n = Number of occasions during the period of tidal record on which the height, H, was attained or exceeded.
N = Total length of tidal record used in the study, in years.
n/N = Average number of occasions per year on which the height, H, has been attained or exceeded.

Table 7.3. Projected heights (m O.D.) of abnormally high tidal levels with particular return periods

Return periods (years)	200	100	50	20	10	1
Heysham	6.40	6.33	6.25	6.15	6.10	5.83
Fleetwood	6.59	6.47	6.35	6.19	6.03	5.66

Table 7.4. Return periods of annual maximum water level (from Graff, 1981)

Return periods (years)	250	100	50	20	10	5	1
Heysham	6.68	6.55	6.43	6.28	6.17	6.05	5.76
Fleetwood	6.20	6.13	6.09	6.01	5.93	5.85	5.56

Table 7.5. Fresh water flows from the four major catchments (in cumecs, from Oct. 1983 to Sept. 1984) (data from the North West Water, River Divisions)

	Oct	Nov	Dec	Jan	Feb	Mar
Leven	599	633	649	668	435	528
Kent	193	179	204	173	86	164
Lune	1728	1550	1913	2685	823	1554
Wyre	276	304	344	291	174	253
	Apr	May	June	July	Aug	Sept
Leven	267	182	168	173	310	406
Kent	60	52	54	52	72	107
Lune	614	526	515	537	928	1132
Wyre	120	63	76	82	147	148

the Bay over 600 cumecs and up to 2000 cumecs at average during winter and spring seasons (Table 7.5.)(data from the North West Water). Such large amount of fresh water flows may enhance the local water levels in the lower reaches of the estuaries when they meet the tides. It is reported, for example, that a flow of 650 cumecs over the Teddington Weir in the Thames could raise the water level at London Bridge approximately 0.3 m higher than prediction (the Admiralty Tide Tables, 1989).

Secular sea-level changes in the past century

Evidence of sea-level changes in the past century have been reliably recorded by direct measurements of tide gauges. Within Morecambe Bay, there are two temporary tide gauges, one in Morecambe and one in Barrow, and two still in operation in Heysham (since 1940) and Fleetwood (since 1930) (Graff, 1981). There are breaks (1942, 1953-1958, and 1973) in the tidal records in Heysham, and breaks (1932-1934, 1963-1964, and 1974) in Fleetwood. But the missing data from one can be substituted by the other. The Proudman Oceanographic Laboratory has provided data of annual mean and maxima of sea level for the present study.

Data of annual mean sea-level for the periods of 1962-1968 and 1975-1988 at Heysham are available (data from the Proudman Oceanographic Laboratory). A simple least-squares fit to these data suggests that mean sea-level at Heysham has risen at a rate of 1.37 mm/yr for 1962-1968 and of 0.74 mm/yr for 1975-1988.

Based on the data sets of annual maximas of water level recorded in Heysham (1940-1990) and Fleetwood (1930-1983), the secular trend of the annual maximum level in the recorded period were calculated. The results of the simple least-squares fit for Heysham and Fleetwood are listed in Table 7.6. It is suggested that the secular trend of the annual maxima of water level in Morecambe Bay is positive at a rate of 1.90-2.50 mm/yr which has happened in the past 50 years. If the crustal uplift continues , the visible rate of rising annual maximum water level will be about 2.20 - 2.80 mm/yr. The trend in annual maxima, therefore, may not be the same as that of mean sea-level.

Table 7.6. Regression coefficients of annual maxima of water level in Heysham and Fleetwood

1. Relative rise in annual maxima of water level		
Heysham	1940-1990	H (m O.D.) = 0.8887 + 0.0025 Y (Year) i.e. the rate is 2.5 mm/yr
Fleetwood	1930-1983	H (m O.D.) = 1.9996 + 0.0019 Y (Year) i.e. the rate is 1.9 mm/yr
2. Actual rise (crustal uplifting rate for the last 4000 years is assumed as 0.30 ±0.12 mm/yr, Shennan, 1989)		
Heysham		2.50 + 0.30 = 2.80 ±0.12 mm/yr
Fleetwood		1.90 + 0.30 = 2.20 ±0.12 mm/yr

7.2.2. Coastal sedimentation

The most significant feature in geomorphology of Morecambe Bay is the extensive intertidal sands which are exposed at low tides and extend for about 303 km^2, from Mean Low Water to the Mean High Water as shown in the O.S. maps (Fig. 7.2.).

Sedimentary pattern

In subtidal areas, the sediments are characteristically fine-grained sands and silts with increasing sediment size grades of fine and medium sands from outside to the central part of the Bay. Gravelly sand and gravel occur on the north side of the mouth of the Bay, where exposures of till on the sea bed exist (Fig. 7.5.)(Tooley, 1985b).

In the intertidal zone, sand banks dominate the central part of the Bay and at the mouths of the estuaries feeding the Bay. They are cut by tidal channels. These sand banks and tidal channels are highly mobile, capable both of slow, steady lateral movements and of sudden sideways shifts of several kilometres during a few tidal cycles, due to the instability of the intertidal hydrology (Pringle, 1987). The rapid movements occur especially in the inner part of the Bay during maximum spring tides and westerly storm conditions. The predominant type of sediment found on the banks is very fine and fine sand (Anderson, 1972). On the northwest and southeast coasts of the Bay, the landward margin of these sand banks, or sandy beaches is associated with shingle which is scattered along the upper zone of the beaches (Photo 8). Along the north and southeast coasts of the Bay and within the estuaries of the river Leven, Kent, Lune and Wyre, the sand beaches merge onto salt marshes at the top of the intertidal zone (Photos 1-7). Silt and mud flats occur only at the heads of the estuaries in Morecambe Bay and in sheltered, low energy environments (Anderson, 1972).

On the basis of relatively intensive investigation on the particle size of the intertidal sediments, carried out between March 1968 and September 1969, Anderson (1972) described the median particle diameter of the sediments in Morecambe Bay ranging between 20 and 210 microns. She indicated that sediments with a median particle diameter of 80 microns or less occur above 1.8 m O.D., which means that tidal forces are the main agents affecting the distribution of sediments in the Bay.

Sediment movement

Within Morecambe Bay, a range of different techniques has been used to study sediment movement, including Admiralty Chart analysis, the use of sea-bed drifters and radioactive tracers. Through the analysis of 11 editions of Admiralty Chart No.2010 Morecambe Bay, Kestner (1970) deduced a series of movements in the tidal channels and sand banks between 1845 and 1968. By 1950 Heysham Lake (a deep tidal channel near Heysham Harbour) had been so reduced in width and depth that for the first time since before 1884, the 9m isobath was not continuous there. By 1968 this trend had so continued that the 5.5m isobath was discontinuous and Heysham Lake had never been so narrow and shallow since surveys began in 1845. Kestner (1970) explained that these changes were produced by the south-eastward movement of a large sandbank into Heysham Lake almost completely blocking the approach channel to the harbour at low water.

Analyzing the same charts, Pringle (1987) described that between 1845 and 1884 depths in Heysham Lake increased from 5.5 m to 9 m as a wide, shallow channel becoming narrower and deeper. The decrease in width continued throughout the period covered by all these charts, but by 1899 the depths had begun to decrease. The cause of these changes was the steady and continuous sideways travel of the First New Grange Channel and the First Clark Wharf Spit from north-west to south-east into Heysham Lake. As is common in such loose boundary hydraulics, one cause, the steady advance of the sandbank, brought about two opposite effects: first an increase in channel depth and secondly as more sand was brought in, marked shoaling occurred. The rate of movement was variable but between 1845 and 1968 giving an overall average of 30.5 m per year during the 123 year period. This process of south-eastward sediment movement seems to have coincided with the slowly eustatic rise with a rate of 1.7 mm/yr in the period from 1840 to 1930 followed by a slightly eustatic fall from 1930 to 1950 in particular (Mörner, 1973).

Two sea-bed drifter investigations were carried out in Morecambe Bay in 1965-1967 (Phillips, 1968), in which Woodhead sea-bed drifters of standard design were used. In the first investigation, the releases were made on an ebb tide so that the powerful initial drift would take them into deeper water just beyond the entrance to the Bay. The recovery rate was 36 percent and the recoveries from all release points were strongly concentrated around the southern end of Walney Island and the adjacent smaller islands, and along the south Furness coast. In the second investigation, the releases were made in the early part of the flood tide so that initially they would be carried towards the head of the Bay. The recovery rate was 76 percent and the recovery pattern from all release points showed a marked concentration along the eastern coast of the Bay and on the extensive sandbanks south of the Cartmel peninsula. It means that within Morecambe Bay, sediment moves in a clockwise fashion during the ebb tide, and anti-clockwise during the flood tides, which is the same pattern as the movement of tidal currents.

7.2.3. Coastline and saltmarshes

Coastlines in this study are referred to the Mean High Water lines which are digitised from the 1:25,000 O.S. maps. The coastlines around Morecambe Bay, from the south-east point of the Walney Island to the north-west head of Fleetwood, including the tidal sections of the four major rivers, are then measured as about 210.5 km in length. On the basis of the geomorphological features of their cross-section profiles from seawards to landwards, these coastlines fall into five groups. Their distribution is summarised in Table 7.7. and Figure 7.6. and their features are described in the following:

1. Sand bank - Shingle - Solid rock. This type of coastline is found typically along the north-west coast of the Bay. Along the cross-section profiles, there is a narrow shingle belt lying along the MHW mark or upper beaches.
2. Sand bank - (shingle) - Embankment. This sort of coastline is protected or restricted by sea embankments, and is commonly found along the south and east coasts. There is a little shingle scattered on the upper zone of sandy beaches.
3. Sand bank - Saltmarsh - Solid rock. This type of coastline lies normally on the sheltered sides of the solid head-land, where saltmarshes are prevented from direct attack of waves.
4. Sand bank - Saltmarsh - Embankment. This is a most common type of coastline along the areas in front of coastal lowlands, which can be found on both sides of the estuaries and many embayments.
5. Sand bank - Saltmarsh - Sand dune. This type of coastline is found only on the east side of the Walney Island.

Types 1 and 2 comprise about half of the total length of the coastlines, and are characterised by sandy beaches along the high water mark, backed by solid rock or embankments. Contrast, the main feature of Types 3-5 is that there is saltmarshes fringing along the margin of intertidal zone.

Table 7.7. Classification and length (km) of coastlines around Morecambe Bay

Type	N.W.	Leven	Coastal sections* Cartmel	Kent	East	West	Total
1	21.0	5.0	8.5	5.0	9.5	5.0	54.0
2	3.0	1.0	1.0	2.5	12.5	15.0	35.0
3	2.0	2.0	1.5	2.0	9.0	5.5	22.0
4	0.0	17.0	6.5	17.0	28.0	24.0	92.5
5	7.0	0.0	0.0	0.0	0.0	0.0	7.0
Total	33.0	25.0	17.5	26.5	59.0	49.5	210.5

* N.W. --- the north west coast from the south-east point of the Walney Island to Wadhead Hill north to Ulverston Sands;
Leven --- the Leven Estuary from Wadhead Hill to Lenibrick Point south to Cark;
Cartmel --- the Cartmel Peninsula from Lenibrick Point to Blawith Point north to Grange-over-Sands;
Kent --- the Kent Estuary from Blawith Point to Blackstone Point west to Arnside;
East --- the east coast and the Lune Estuary from Blackstone Point to Plover Hill on the mouth of the Lune;
South --- the south coast and the Wyre Estuary from Plover Hill to Rossall Point in Fleetwood.

The existing saltmarshes

There were large area of saltmarshes and coastal mosses in Morecambe Bay, lying below 5.5 (the southern part) and 6.1 (the northern part) m O.D., which have been reclaimed since the earliest sea-banks were built in the area in the 13th century (Gray, 1972). Recently, the Bay has progressively been silted up with development of saltmarshes outside the embankments. Gray (1972) indicated that there has been a progressive overall growth of salt marsh, over

800 ha. having accreted since 1888 mainly at sites along the east shore and below the Cartmel peninsula, associated with phases of erosion alternating with growth. The rate of salt marsh growth has clearly been accelerated by reclamation attempts and the training walls may reduce the erosional processes by stabilizing the tidal channels (Gray, 1972)

The latest survey (Gray, 1972) stated that, in the northern part of Morecambe Bay from Morecambe around the coast to Aldingham, there are some 1485 ha. of vegetated land subject to periodic tidal submergence. These vegetated lands comprise a number of marshes and saltings. Measured currently from the 1:25,000 O.S. maps (from the Ordnance Survey, 1976-1987), saltmarshes within the Bay and its four main estuaries occupy about 47.4 km^2 (see Fig. 8.2.).

Erosion of the saltmarshes

The retreat of saltmarshes is different from sand beaches, because they do not maintain an equilibrium profile with sea-level changes. There is no compensation within short-term cycles.

Based on a study of old estate maps, O.S. maps, and both well-documented and anecdotal accounts at Silverdale, Gray (1972) illustrated that (a) in the 1840s Silverdale was a popular bathing resort but this activity declined in the 1850s as the foreshore became muddier and by 1861 a small area of marsh had developed, associated with the movement of the Kent channel to a position close to the Grange shore; (b) there were extensive saltmarshes at

Silverdale by the year 1893, but these marshes were almost destroyed as the Kent tidal channel swung back to the Silverdale shore; (c) since 1915 when the channel returned to the Grange shore, saltmarshes have continued to develop in front of Silverdale.

In a more recent study of air photographs, Pringle (1987) indicated that the saltmarsh at Silverdale had been extending and accreting since early this century, when the main Kent channel lay close to Grange. However in the late 1970s, this accretion of marshes was sharply reversed, as the main Kent channel moved eastward close to the edge of the Silverdale saltmarsh which suffered rapid erosion. In 1987, there were saltmarshes of only about 200 m in width remaining there, according to the present study.

Thus it was suggested that the development of saltmarsh had been subject to variations of the low-water channels which may produce alternating phases of erosion and accretion in any locality (Gray, 1972; Pringle, 1987). Beside this sort of lateral movement of tidal channels causing erosion of saltmarshes, loss of sediment supplies from adjacent areas could also affect marsh accretion (Hackney and Cleary, 1987; Jacobson, 1988).

Allen (1989) investigated the evolution of saltmarsh cliffs of British west-coast estuaries. He estimated the horizontal retreat rates of marsh cliffs in the systems of Severn Estuary, Morecambe Bay, and Solway Firth, as high as 1 m/yr. A similar measurement at Stoke Marshes in the Medway suggested a mean rate of marsh cliff retreat as 0.8 m/yr, with variation from 0.1 to 3.2 m/yr (Kirby, 1990).

7.2.4. Projected sea-level rise in the next century

This section aims to assess the likely sea-level trend in Morecambe Bay over the next century by applying the scenarios which are discussed and indicated by Hoffman (1984) and the IPCC report (Warrick and Oerlemans, 1990).

In a global view, Table 6.1. provides two scenarios of eustatic sea-level rise for the next century. It is assumed that the global trend of sea-level rise in the next century can be referred to the northern Atlantic and the Irish Sea. In Morecambe Bay, the rising mean sea-level may be a little slower than the global one due to the glacial isostatic factor (uplifting) for the Bay (Shennan, 1989) and the factor of geoidal configuration for the British Isles (Clark and Primus, 1987). By subtracting the uplifting value and the geoidal changes, two scenarios for sea-level rise in the next century can be given in Table 7.8., and the magnitude to which the sea-level is likely to reach by that time is also given.

Table 7.8. Sea-level scenarios for Morecambe Bay

(Rates, mm/yr)	1990-2000	2000-2050	2050-2100
Scenario 1	4.3	5.1	6.7
Scenario 2	5.7	10.1	21.9
(Magnitude, m)	1990-2000	2000-2050	2050-2100
Scenario 1	0.043	0.298	0.633
Scenario 2	0.057	0.562	1.657

As in the previous discussion, a sea-level rise of over 20.0 mm/yr is likely to occur by the end of the next century, provided that an extreme condition is reached, which actually happened in about 8000 B.P. At least, rates around 10 mm/yr are possible to be reached by the year 2050. These rates have been experienced in Morecambe Bay over the past 7000 years, and commonly in other coastal sectors around the British Isles (Tooley, 1974, 1978a, 1982; Shennan, 1986b; Devoy, 1979).

7.2.5. Coastal responses to the rising sea-level

Increases in mean sea-level (saying less than 2 metres) are a small proportion of water depth in the northern Atlantic, and therefore seem to have little effect to the existing marine hydrological regime. However, the implication of it may be very big for the marginal areas such as the northeastern Irish Sea.

Future changes in hydrological conditions

In contrast to the Thames estuary, Morecambe Bay is a multi-estuary system. There are two significant features in the morphology of the Bay which are different from the Thames Estuary. One is that half of the Bay dries out during low tides. The other is that the present MHW is not fully restricted by sea defences and solid rocks along some of the coastal sectors (Fig. 7.6.). The area that dries out is dominated by tidal flats and saltmarshes. Changes in tidal range and level resulting from the rising sea-level in the next century would therefore be much more complicated.

Providing no change in sedimentation and erosion, there would be two likely consequences of a rising sea-level in Morecambe Bay: 1. part of the tidal flats that used to dry out will submerge permanently; 2. more areas such as the mature marshes will be inundated during high tides, i.e. the intertidal zone becomes wider (Fig. 7.7.). The latter could result in a decrease of tidal range. The magnitude of decrease in tidal range would be a function of the enlargement in area of the intertidal zone, i.e. changes in sea bed morphology.

On the basis of the present relationships, in summary, a rising sea-level could reduce the tidal range but widen the intertidal zone in the northern and southeastern parts of the Bay. However, in the southwest part of the Bay, tidal range still could slightly increase. For Morecambe Bay as a whole, high-tide levels will be raised at the same rate as that of the rising mean sea-level during the next century.

In Morecambe Bay, tidal waves will still be very asymmetrical due to the shallowing morphological feature of the northern and southeastern intertidal zones being maintained.

If the morphological features remaining unchanged and sea level rising at a small rate as Scenario 1 (Table 7.8.), the pattern of tidal streams, anti-clockwise during flood tides and clockwise during ebb tides, will be continued. The direction of tidal residuals will therefore be the same as the present ones, but the maximum velocity of the residuals would move landwards and still close to the future low water mark as it used to be. Dyer (1986) explained that as the tide rises to cover the flats a large volume of water has to flow through a small cross-sectional area with, obviously, a high velocity. Once the flats are covered the velocity will be reduced because of the increased cross-sectional area. It seems that the situation Dyer (1986) explained will be continued in the next century.

If sea level rises at a high rate as Scenario 2 (Table 7.8.) and there are no further improvement such as armouring and raising the freeboard, high tides would breach or overtop the existing sea embankments (see Chapter VIII for details). As a result, the geometry of the Bay would change significantly, and the tidal pattern and residuals could be profoundly affected (Flather and Heaps, 1975).

The consequence of changes in marine hydrology caused by sea-level rises in the next century will be significant. These changes will affect the sedimentary dynamics, which are discussed in the following sections.

Future changes in sedimentation

In Morecambe Bay, a rise in sea level could move the intertidal zone landwards, providing a rate of rising sea-level higher than that of intertidal sedimentation. If sea level rises at a low rate as Scenario 1, more supertidal areas in the Bay will be inundated and the intertidal zone at Cartmel and Silverdale Marsh could become wider. Because the projected rising sea-level does not seem to be able to change the tidal pattern and the deepening in sea water may enhance the velocity of flood streams, more amount of suspended sediments could be carried by flood streams from the sea onto the up-estuary parts of the Bay, and deposit them on to the upper part of the tidal flats and on to the surface of the existing saltmarshes in particular.

If sea level rises at a higher rate as Scenario 2 during the second half of the next century in particular, flood streams could be even able to carry and deposit clastic sediments onto the reclaimed lands, if sea embankments are breached. But, if the sea embankments are maintained or increased in height, an increase in tidal current velocities could induce erosion of the embankments. In the other way, the seaward trend of intertidal sandbank movements will become adverse, i.e. the faster sea level rises, the slower the seaward movement will occur or even be adverse.

Beaches such as those in Morecambe, Heysham and Grange are major components in the recreational use of coasts. Beaches are unlikely to disappear completely with rising sea-level, but the nature of beach material may become coarser. Without human intervention, beaches will gradually migrate landwards as sea level rises. However, in the case of Morecambe, the beach is backed by a concrete seawall. The beach level might rise due to the piling up of material against the seawall, providing sufficient supply of sediments. During storms, the beach level will fall due to the increased erosion.

Prospects of the saltmarshes

Two examples - Pilling marsh and Roudsea Wood - could be examined. In Pilling marsh, the seaward edge of the mature marshes is being eroded

(Photo 3) and remains about 200 - 800 m in width (Figs. 7.7. and 7.8.). Such erosion seems likely to continue as sea level rises at Scenario 1 and will be more rapid if sea level rises as Scenario 2. It is assumed that an erosion rate of 5 - 10 m/yr (as experienced in Silverdale Marsh during the last ten years, see Pringle 1987) would be reach during the first half of the next century associated with a rise in sea level of Scenario 2. If so, 50 or 70 percent of the remaining marshes would be erode away by the year 2050.

In Roudsea Wood, due to the sheltered position close to the head of the estuary, erosion of the saltmarshes would not be as serious as in Pilling marsh. The main impact to the rising sea-level would be of landward migration of the vegetation zones as shown in Figure 7.8.

Impacts of sea-level rise on saltmarshes in Morecambe Bay could therefore be assumed as follows:

(A) during the period from the present day until 2050:

(A-1) the nature of the present saltmarshes would be maintained as sea-level rises at a low rate (less than 5.0 mm/yr, Table 7.8.). This means the vertical accretion of the existing saltmarshes could keep pace with the rising sea-level. But the erosion at the seaward edge of the marshes would also be continued. The rate of such retreat will depend upon the lateral movement of tidal channels in front of them and changes in sediment budget. The saltmarshes will become narrower along the coasts.

(A-2) If sea level rises at the high rate (6.0-10.2 mm/yr), the present pioneer zones and low-level saltings (Gray and Scott, 1987) will seriously retreat. In the later part of this period, the present high-level saltings at 4.7-5.8 m O.D. which used to be flooded by 10-100 tides a year (Gray and Scott, 1987), will likely to be flooded by 150-220 tides a year. The mature marshes at 5.3-6.6 m O.D. will receive a doubling in the number of floodings a year than previously 0-40 floods a year. This means that the areas currently occupied by mature marsh will become high saltings. If there are embankments restricting saltmarshes migrating landward, the mature marshes on seaward side of the embankments would hardly survive.

(B) During the period from 2050 to 2100:

(B-1) a slowly rising sea-level (Scenario 1) would induce the same result in salmarshes as the (A-2) mentioned above.

(B-2) If sea level rises at a high rate as Scenario 2, most of the existing saltmarshes, such as those at Pilling Marsh and Silverdale Marsh and those around the Cartmel Peninsula, will be overlaid by clastic sediments. The seaward front of embankments and solid rocks will be under direct attack from sea waves.

In short, most existing saltmarshes could keep pace with the rising sea-level before the year 2050, except in some places with inadequate sediment supply or where they are affected by lateral movement of tidal channels otherwise. While beyond the year 2050, most existing saltmarshes will likely be overlapped by marine clastic sediments, and only some spots of saltmarshes and saltings could be found in the heads of the estuaries.

7.3. The Thames Estuary

In contrast with the geometry of Morecambe Bay which is a broad, complex and multi-estuarine system, the Thames Estuary is a relatively simple, long and narrow estuary. Here, the tidal Thames is defined as a self-contained system, bounded to the west by the tidal limit at Teddington Weir and at the seaward end by an arbitrary line joining Southend and the Isle of Grain. In this section, the present hydrological conditions, coastal sedimentation, coastline features and saltmarshes are to be illustrated. The likely responses of these coastal features are also discussed in this section.

7.3.1. Present hydrological conditions

The hydrological features in the Thames Estuary have been well recorded during this century by instruments of tide gauges. Within the Estuary, there are eight important tide gauges (Fig. 7.9.).

Tidal pattern and levels

Although both Morecambe Bay and the Thames Estuary are under macro-tide regime, the tidal pattern in the Thames is more simple with a one-dimensional current; up-stream during flood tides and down-stream during ebb tides. The tide running into the Estuary is diurnal, and is generated in the area around the amphidromic point in southern part of the North Sea, which propagates southwards and enters the Estuary (Pethick, 1984). Significant tidal levels are calculated from the tide gauges along the Estuary (Table 7.9.).

It is clear that the high tide levels are raised from Southend to London Bridge about 0.7 m (MHWNT) or 1.1 m (MHWST). Further upstream at Richmond, the raised high tide levels may partly be enhanced by the discharge of fresh water entering over Teddington Weir (Bowen, 1972). In contrast, the low tide levels become a bit lower from Southend to London Bridge, which means the tidal range is increased with distance in the lower Thames. The causes of the increase in tidal range and height of high tide levels is to be discussed in the following section.

At the present day, the maximum instantaneous discharge during flood or

Table 7.9. Tidal levels in the Thames Estuary (m O.D.)
(data from the Admiralty Tide Tables, 1989)

Tide gauge	HAT	MHWST	MHWNT	MLWNT	MLWST	MTL
Southend	3.50	2.80	1.90	-1.50	-2.40	0.12
Thames Haven	3.93	3.15	2.15	-1.65	-2.55	0.10
Tilbury	3.98	3.28	2.18	-1.52	-2.62	0.13
Woolwich	4.45	3.65	2.35	-1.65	-2.85	0.32
London Bridge	4.88	3.90	2.60	-1.60	-2.70	0.50
Chelsea Bridge		3.86	2.66	-1.44	-2.24	0.71
Barnes Bridge		4.13	2.73	-0.87	-1.37	1.15
Richmond Lock		4.39	2.99	-0.41	-0.41	1.64

ebb of a spring tide through a cross-section of the Estuary at Southend is about 1,500,000 cumecs, and 450,000 cumecs at Tilbury, 150,000 cumecs at Barking, and 50,000 cumecs at London Bridge (Inglis and Allen, 1957). In contrast, the average discharge of upland fresh water flows which enters the Estuary at Teddington Weir is only about 2500 cumecs, and the flows of various tributaries that enter the Estuary below Teddington are small by comparison (Inglis and Allen, 1957). Although the fresh water flows from upland catchments are much smaller than the tidal streams, they could effectively raise the local water table. It is reported (the Admiralty Tide Tables, 1989) that a flow of 650 cumecs over the Teddington Weir in the Thames could raise the water level at London Bridge approximately 0.3 m higher than prediction.

The tidal streams between Canvey Island and London Bridge vary locally but maximum velocities are approximately the same at 1.22 ms-1, slightly higher than those in Morecambe Bay. Similarly, the difference in salinity between bed and surface in the reaches between Canvey Island and Woolwich is small, barely exceeding 1 part/thousand by weight, which means that the water in the Estuary is mixing well.

Secular trend of the tidal regime

In 1899 the range of springs at London Bridge was only 4.57 m (15 feet); so that in the last three-quarters of a century, the increased oscillation is 1.75 m (5 feet 9 inches)(Bowen, 1972). Of the increased range of 1.4 m (4 feet 7 inches) as compared with Sheerness, 1.17 m (3 feet 10 inches) are due to the elevation of the surface at high water, and 0.23 m (9 inches) to the depression at low water. Comparing with the tidal levels given in Table 7.9., this conclusion provides a strong expression that the tidal regime in the Estuary has been enhanced dramatically in the last one or two centuries. Recently, Rossiter (1972) estimated the secular variation of mean sea-level in the U.K. and suggested a reliable value of the secular variation in Southend as 3.4 mm/yr. However, Rossiter's result only provided information about the relative sea-level trend in the period of 1929-1963, without giving implications of the large increase in high tide levels, particularly to their importance in determining flood defence levels (Bowen, 1972).

Based on a more detailed data set from the tide gauges in the Estuary, Bowen (1972) performed a multiple regression analysis with consideration for the fresh water flow over Teddington. The results of his calculation are listed in Table 7.10A. Although the results contain big standard errors, Bowen's analysis provided a clear picture about the influence of fresh water flow to the high tide levels which occur only at the tide gauges upstream from Tower Pier to Teddington. From a more detailed examination of the Tower Pier data (Table 7.10B.), Bowen (1972) suggested that the levels of MHW were increased much more quickly (about 6.5-7.6 mm/yr) than those of MLW (about 0.3 mm/yr), as mean sea-level rose (about 3.6-4.1 mm/yr). This evidence is very important in projecting the future local rise in high water level as mean sea-level rise in different scenarios. Therefore, it is necessary to find out the possible causes of the increased tidal amplitude and levels. Bowen (1972) has

Table 7.10. Regression analysis of the annual MHW and MLW (from Bowen, 1972)

(A) Tide gauge	Regression coefficients MHW (mm/yr)	MLW (mm/yr)	Correlation water level/flow
Southend	3.51 ±4.3	2.50 ± 4.6	0.282
Tilbury	3.81 ±5.8	2.77 ±17.4	0.376
Woolwich	6.30 ±8.2	-0.52 ±13.4	
Tower Pier	6.80 ±4.9	0.43 ± 4.0	0.682
Chelsea	5.88 ±8.5	-0.88 ± 8.2	0.665
Richmond			0.735
Teddington			0.872

(B)	Regression coefficients at Tower Pier (mm/yr)	
mean high water springs	7.58 ±6.1	1934-1968
mean high water neaps	6.51 ±6.4	1934-1968
mean low water neaps	0.34 ±4.3	1934-1967
mean low water springs	0.24 ±5.5	1934-1967
amplitude, springs	3.87 ±3.4	1934-1967
amplitude, neaps	3.26 ±3.4	1934-1967
mean level, springs	4.11 ±4.6	1934-1967
mean level, neaps	3.60 ±4.3	1934-1967

concluded that these increases fall essentially into two categories, natural and artificial. For the natural causes, Bowen (1972) suggested that the most physical explanation for the increase in tidal amplitude would be an association with the other change, the secular trend (in mean sea-level). In fact, the deepening of sea water does reduce the sea-bed friction, and also a deepening of the North Sea may have an effect on the tidal input to the Estuary and consequently give an increased tidal amplitude upstream, at London Bridge for example.

The artificial causes include the major engineering work: maintenance and capital dredging, building or removal of bridges and piers, and reclamation and embankments (Bowen, 1972). For instance, a major capital dredging programme between 1909 and 1928 deepened the channel upstream from

Tilbury. The consequence was an increase in the rate of tidal propagation and increase of tidal range in the upper reaches. At London Bridge low water was lowered by about 15 cm (6 inches) and high water raised about 5 cm (2 inches) (Inglis and Allen, 1957). The effect of bridges and piers is rather difficult to determine (Bowen, 1972), and there is no evidence of changes that would give a more or less steady change in the tidal regime. However, embanking is itself a more or less continuous process. The continual reclamation and the straightening, smoothing and raising of the banks would reduce both the effective viscosity of the Estuary and the total tidal prism.

Extremely high water levels

Frequency of occurrence of abnormally high sea levels on the east and south coasts of England was analysed by Suthons in 1963. From a statistical examination of past tidal data, annual tidal maxima were recorded from Sheerness and Southend for a period of 1819-1953. Suthons (1963) estimated the probability distribution of their return periods. Suthons' estimation (1963) suggested that if one extrapolates the straight lines through the points of the annual maximas at the lower levels the return period of the 1953 high level (4.6 m O.D. at Southend and 5.41 m O.D. at London Bridge) appears to be roughly about 200 years. However, the return period of the 1953 level, allowing for a constant rise in mean sea-level of 1 ft/century (3.28 mm/yr), was then only about 60 years ! Pugh (1990) gave a similar suggestion that the present '100-year return' level at Sheerness will return in a period of 60 years.

Comparing the trend of mean sea-level with that of the annual maxima, both being calculated in 10-year running means in order to reduce the fluctuations from year to year, Suthons (1963) indicated that the fluctuations are still much greater than those of mean sea-level. From his plots (1963), it is implied that a slight increase in mean sea-level could double or even triple the height of the maximum level.

Using a more recently updated data set, Graff (1981) assessed the return period of the annual maximun levels and indicated that the 1/100 year frequency level for Southend was expected to reach about 4.52 m O.D. The levels for other return periods can be read from his diagram (1981) listed in Table 7.10.

Due to the operation (closure during extremely high tides) of the Thames Barrier, the extreme levels for London Bridge (Table 7.11.) will not be reached in the certain return periods. The values given here are to be a reference.

Table 7.11. Projected heights (m O.D.) of abnormally high water levels with particular return periods (after Graff, 1981)

Return periods (years)	250	100	50	20	10	5	1
Southend	4.72	4.50	4.36	4.17	3.99	3.87	3.52
Tilbury	5.02	4.82	4.68	4.49	4.34	4.21	3.90
London Bridge	5.48	5.32	5.20	5.07	4.94	4.82	4.52

Sea-level trends in the past century

In the past century, accurate measurement of sea level has been successful by means of instrumental (tide gauge) records. Sheerness, for which records extend back to 1832, is the oldest U.K. station with a tide gauge still in operation today (Woodworth, 1987). Unfortunately, there are several major breaks in the record: 1859-1891, 1928-1950 and several years in the mid-1950s and 1960s. Across the River Thames at Southend, however, there is an almost continuous record since 1929 up to the present, which could nearly substitute for the missing Sheerness data.

Based on a composite of the Sheerness and Southend records, Woodworth (1987) provide a regression coefficient, a simple least-squares fit to the measured annual mean sea-level data: 3.65 ± 0.23 mm/yr for 1916-1962, and 1.01 ± 0.31 mm/yr for 1963-1982, and for the whole period of 1916-1982, 2.27 ± 0.21 mm/yr. A similar figure was also given, 3.3 mm/yr for Sheerness in 1916-1962 by Gordon and Suthons (1963) and 3.4 mm/yr for Southend in 1929-1962 by Rossiter (1972). Pugh (1990) suggested a relatively low figure, 1.94 ± 0.23 mm/yr for the combined data set from Sheerness and Southend in 1916-1982.

It was indicated, however that the extreme levels at London Bridge which represent a major flood risk have occurred only eight times in the last 200 years (Figure 7.10.) (International Disaster Institute, 1981), increasing in height above O.D. at the rate of about 2.4 ft/century (7.6 mm/yr) (Bowen, 1972). The IDI (1981) further suggested that this increase was due, in part, to a sinking of the land in South East England relative to mean sea-level of about 1.1 ft/century (3.61 mm/yr), and an increase of 1.3 ft/century (4.26 mm/yr) in the tidal amplitude at London Bridge. These rates may suggest that the embankments along the Estuary could have restricted the geometry of the Estuary and consequently enhanced the tidal regime (Bowen, 1972). Moreover, the large amount of steel and concrete construction built upon the former intertidal deposits along the present river banks could have enlarged the compaction rates of the sediments underneath (IDI, 1981).

Applying the data set of annual maxima of water level recorded at Southend and London Bridge, provided by the Proudman Oceanographic Laboratory, a regression coefficient is calculated by using the least-squares method, and listed in Table 7.12. If the crustal subsiding factor (Shennan, 1989) is subtracted, the actual rising rate is only about 2.10 - 2.60 mm/yr.

Table 7.12. Regression coefficients of annual maxima of water level in Southend and London Bridge

1. Relative rise in annual maximas of water level		
Southend	1929-1986	H (m O.D.) = -4.1912 + 0.0040 (yr) i.e. the rate is 4.0 mm/yr
London Bridge	1929-1982	H (m O.D.) = -4.2584 + 0.0045 (yr) i.e. the rate is 4.5 mm/yr
2. Actual rise (crustal subsiding rate in the last 4000 years is estimated as 1.90 ±0.32 mm/yr, Shennan, 1989)		
Southend		4.00 - 1.90 = 2.1 +/- 0.32 mm/yr
London Bridge		4.50 - 1.90 = 2.6 +/- 0.32 mm/yr

7.3.2. Sedimentation in the Estuary

Sedimentation in the Thames Estuary has been restricted within the tidal channel by embankments for at least eight centuries (Akeroyd, 1972), and has been investigated in detail, due to the commercial importance of the waterway.

Sedimentary deposition along the tidal channel of the Thames has been disturbed to some extent by artificial construction and capital dredging for navigational purposes.

Sediment distribution

In respect of sedimentation, the Thames Estuary may be divided into three sectors (Prentice, 1972) (Fig. 7.9.). From Teddington to below London Bridge the river carries mainly land-derived sediment; suspension load is low, and deposition on the bed and banks is slight. From Woolwich Reach to Gravesend Reach is a zone of high suspended load and much sedimentation --- the Mud Reaches in particular. Below that, down to Sea Reach, sedimentation is dominated by bed-load transport from the sea. It is indicated (Inglis and Allen, 1957; Kendrick, 1972; Prentice, 1972) that the sedimentary pattern of the Mud Reaches is related to the position of the saltwater-freshwater mixing zone, and so is most sensitive to the relative changes of sea level. The constitution of this mud is widely variable, varying from 80 down to 10 percent of clay, while still retaining its fluid and mobile character. Upstream and downstream from the Mud Reaches, sedimentation becomes more and more silty and sandy (Kendrick, 1972).

At present, the Mud Reaches receive sediment from the higher reaches of the Thames. This consists very largely of finely divided clay sediment carried in suspension, and the presence of hard-bottom in many places above London Bridge indicates that most of it is carried through (Prentice, 1972). On meeting the saline waters, flocculation takes place, and the larger particles which result in less capable of transport. The Mud Reaches also receive some sediment from tributaries though in many cases the flow in reality is derived from the sewage works discharging into them (Prentice, 1972).

Inglis and Allen (1957) estimated that the material carried into the estuary each year by the River Thames and the various tributaries did not amount to more than 15 percent of an average year's dredging. Adding sewage effluents, industrial effluents, and storm water, it is amounted to about 45 or 50 percent of the average year's dredging. They also indicated that the material carried up the estuary may either be previously dredged mud dumped at the Black Deep or fine material eroded from the coastal areas bordering the estuary, particularly on the Kent side.

An attempt has been made to quantify the rate of siltation at selected sites in the estuary. Prentice (1972) explained that a particular tanker berth, known to be subject to heavy siltation, was selected, and the quantity of water below low-water datum in the berth was measured. This investigation suggested that the rate of siltation is much more rapid in the winter months in the upper reaches, and a rapid siltation at Halfway Reach is remarkably associated with the phases of high fresh water flow over Teddington Weir. Conversely, in the seaward zone below the Mud Reaches maximum deposition in sheltered sites occurs in the summer, and the reduced ebb flows produced by dry weather will favour accretion, while the higher ebb flows of winter will produce a net loss of sediment. The pattern therefore appears to be one in which the zone of high deposition moves up and down the estuary in response to the changes of water level. This means high deposition would occur at the reaches upstream from the Mud Reaches during winter, a period of relatively high water, while occurring at the reaches downstream from the Mud Reaches during summer, a low water period.

Sediment movement

Inglis and Allen (1957) suggested that there was a net landward drift of bottom sediment from the sea to the lower end of Woolwich Reach. Studies of heavy minerals and of the distribution of ostracoda carapaces indicated that some outer estuary material reaches higher than this (Prentice, 1972).

Long-term observations suggest (Prentice, 1972) that much of the sediment deposited on the banks of the estuary is eventually returned to circulation. In many places there is a slow accretion of mud between low-water and high-water marks, which eventually becomes unstable, and then slides into deeper water, where it is taken up into suspension again. Prentice (1972) concluded that the erosion velocity was likely to be 0.5 ms^{-1}, and that in the site of deposition the current velocity is below this figure for more than half the tidal cycle, whereas at the erosional site current velocities are greater than this for more than half the cycle.

Experiments were carried out in the estuary in 1954 and 1955 using radioactive tracers (Allen and Grindley, 1957). Scandium 46 was selected as a tracer. The tracer was mixed with fluid mud and released on the bed in

Gravesend Reach just after high water so that the first movement of the tracer was seaward. It was described that the tracer was carried seaward by the ebb current immediately after injection and some of it was deposited at various points between Gravesend Reach and Canvey Island; after the first day there was no evidence of further seaward movement. In the course of its subsequent upriver excursions, largely under the influence of the landward bed-drift, the tracer was detected at a number of places between Gravesend and Barking. The tracer reached the Barking siltation area, 14 miles above the injection point, about 1 week after injection, but no indication of its presence was found upstream of the Mud Reaches at any time.

An interesting parallel experiment was carried out at the same time in the Thames model (Allen, 1952). Hollow celluloid balls were used as indicators of water movements. They were injected at the same point in the estuary and at the same time instant in relation to high water as the radioactive tracers. They gave a good indication of the movement of the water in the layer extending from the bed to about 8 ft above it. The balls travelled successively upstream and downstream with the flood and ebb tides, but their overall movements were landward. This movement continued at a decreasing rate until the balls arrived at the Mud Reaches, when the excursions on flood and ebb were approximately equal and the balls therefore remained indefinitely in the Barking area.

The operation of the Thames Barrier could (more or less) disturb the hydraulic situation and sedimentary dynamic equilibrium. Tests were carried out for physical and numerical purposes by Kendrick (1972). He assumed that the barrier was operated as a half-tide control device, the gates being closed during the ebb tide to impound the water upstream at a certain level and reopened when the following flood tide reached a similar level at the barrier. He concluded the tests that such half-tide control operation of the barrier would radically change the siltation characteristics of the estuary --- either by decreasing depths in the present major deposition zone or by creating a new deposition zone further seaward. The evidence available so far suggests that siltation would be greater, the further down-river the barrier site.

A new measurement to the sediment budget of Medway estuary, one of the major tributaries which flow into the Thames, was recently made by Kirby (1969, 1990). He traced the history of the last 400 years and indicated that the prolonged erosion of the broad salt marshes of the Lower Medway began around 1700 A.D. Kirby (1990) further suggested that accretion on the shrinking areas of salt marsh surfaces is still proceeding, while the salt marsh creeks and cliffs, and the increasing areas of tidal flat surface are all eroding. On the Stock Marshes complex, for instance, the rate of loss of sediment is approximately 160,000 tonnes/yr. He stated that the sediment budget of the entire intertidal zone of the Medway estuary has not been established but could approach 1,000,000 tonnes/yr. There is no evidence that this sediment redeposited subtidally within the estuary. The reason for the dominantly erosional regime has not been established. Possibly, factors such as a decrease in rate of sediment supply to the Medway, resulting from changed agricultural practices to landward and reclaiming of marshes to seaward in the Thames

Estuary, combined with sea-level rising faster than the rate of supply of fine sediment are involved (Kirby, 1990).

7.3.3. Embankments along the Thames Estuary

The first embanking in the Thames dates back to early Roman times, when the Romans developed their settlement of Londinium. As years went by there were occasional high surge tides as the sea in the outer estuary crept ever higher (Gilbert and Horner, 1984). To prevent these areas being flooded by high water levels resulting from high upland flow or surge tides from the sea, flood banks were built. The embanking on the main land Thames marshes had begun by the later 12th century (Akeroyd, 1972); yet the shepherds on Canvey Island in the lower Thames inhabited open saltings, and the islands were apparently not embanked and united until the 17th century (Cracknell, 1959). Undoubtedly there has been full embankments along the coastlines of the Thames Estuary (Akeroyd, 1972) and its major tributary, River Medway (Kirby, 1969), since the 18th century, the Industrial Revolution. At present, the Thames upstream from Tilbury is protected mainly by concrete embankments, yet downstream by soil and stone-armouring embankments, except Canvey Island and its adjacent areas in which concrete embankments were built along the front of the Island but not the tidal creek behind it.

These embankings have narrowed and restricted the tidal channel of the Thames, so that there are only pieces of narrow intertidal flats (less than 100 m in width) existing along both sides of the tidal channel upstream from Tilbury. However, there are extensive intertidal flats, associated with saltmarshes lying on their upper parts, on the lower reaches of the Thames and the Medway.

7.3.4. Saltmarshes

In the Thames Estuary, a number of large areas of saltmarsh have been reclaimed since the Roman Times for agricultural purposes (Akeroyd, 1972). However, as the rise in relative sea level induced marine sediments to be laid down overlying the former marshlands (Devoy, 1979), many Roman sites were buried about 4 m below the present ground level (Akeroyd, 1972). As long as the sea had been able to flood over the low-lying ground, the silt carried down by the flood water from the North Sea and river discharges had been deposited as sea water spread over the marshes and the flow velocity slackened. The silt slowly but steadily raised the level of marsh, keeping pace (more or less) with the rising sea level (Gilbert and Horner, 1984). The largest scale of saltmarsh reclamation was made during the 17th century, especially when the shepherds came to the lower Thames, such as Canvey Island, Cliffe Marshes, and Sheppey Island.

On the 1:25,000 O.S. maps (1976-1987), saltmarshes on the lower Thames occupy about 24.5 km^2, most of them locate at River Medway, the Swale, and around Canvey Island (see Fig. 8.10.).

Kirby (1990) reported his measurements at some marshes in the Medway. He indicated that accurate calculations of the mass of material abstracted from the estuary by the salt marshes is made difficult, not only by the variation of the rate of accumulation from marsh to marsh, but also because the precise area of salt marshes is difficult to measure due to the fragmentation of the marshes and the tessellated nature of the coast. His measurements showed an average rate of marsh accretion for Stoke Marshes as 2.61 mm/yr, whilst 5.54 mm/yr for Millfordhope Marsh. For a new marsh which locates at the head of a tidal creek at Bedlam's Bottom, an average rate is given as high as 12.89 mm/yr. He suggested that the sedimentation rates obtained for Stoke Marshes probably represent the best average for a natural marsh in the Medway, since its level is least influenced by humans.

A measurement at Stock Marshes in the Medway (Kirby, 1990) suggested the marsh cliffs were retreating at a rate of 0.8 m/yr with variation from 0.1 to 3.2 m/yr. This horizontal retreat of marsh cliffs seems to coincide with the rise in mean sea-level.

7.3.5. Scenarios of sea-level rise in the next century

Sea-level scenarios in Table 6.1. are also applied to the North Sea, based on the assumption that the mean sea-level change in the next century in the North Sea will generally follow the trend of the global mean sea-level. In a regional view, however, the factor of land subsidence which could affect the observed sea levels in the lower Thames Estuary as well as the geoidal changes should be taken into account. From Table 6.1. therefore, the sea-level scenarios for the Thames Estuary at Southend in the next century are given by adding the value of land subsidence which is presumed to be 1.90 mm/yr (Shennan, 1989). The results are listed in Table 7.13.

Table 7.13. Sea-level scenarios for the Thames Estuary

(Rates, mm/yr)	1990-2025	2000-2050	2050-2100
Scenario 1	6.6	7.3	8.9
Scenario 2	7.9	12.3	24.1
(Magnitude, m)	1990-2000	2000-2050	2050-2100
Scenario 1	0.066	0.431	0.876
Scenario 2	0.079	0.694	1.899

7.3.6. Likely changes in the intertidal zone

Increases in mean sea-level (saying less than 2 metres) are a small proportion of water depth in the northern Atlantic, and therefore seem to have little effect to the existing marine hydrological regime. However, the implication of it may be very big for the marginal areas such as the southern North Sea. In fact, the southern North Sea basin is subsiding (Shennan, 1989).

Future changes in hydrological conditions

On the basis of these principles illustrated in section 7.1., a rising sea-level could increase tidal amplitude and move the line of maximum tidal amplitude up-estuary. However, such impacts on the Thames Estuary and Morecambe Bay would not necessarily be the same, due to difference in their geometries and morphologies.

In contrast to Morecambe Bay, the Thames Estuary is a long and narrow tidal channel, and is fully restricted by embankments. The river bed around the point of maximum tidal amplitude is not dried out during low tides due to the fresh water flow from upstream. Therefore the Thames Estuary could be easily expressed as a one dimensional model to examine the likely change in tidal amplitude as sea-level rises. At the present, the tidal amplitude between MHWST and MLWST increases from 5.2 m at Southend to 6.6 m at London Bridge, and beyond this point decreases to 4.8 m in Richmond Lock (Bowen, 1972). The distance at which the maximum point will move appears to be a function of the increasing (tidal amplitude) rate against the magnitude of rising sea-level, depending upon the slope of the water surface along the longitudinal profile. It is thus assumed that the point of maximum tidal amplitude could move further upstream probably to Barnes Bridge as sea level rises only one metre by the latter half of the next century. The closure of the Thames Barrier will prohibit tidal waves moving upstream otherwise. It is difficult to quantify accurately how much the tidal amplitude will be enhanced in such a well confined area providing a given scenario of sea-level rise, without refined numerical modelling. Before the modelling is achieved however, the secular trend of tidal levels may provide some clues. For instance, from Bowen's calculation (1972), during the period of 1934-1968, the tidal amplitude at Tower Pier (London Bridge) increased at a rate of 3.87 $\pm$3.4 mm/yr (Springs) and 3.26 $\pm$3.4 mm/yr (neaps), which is associated with the rise in relative sea-level at a rate of 4.11 $\pm$4.6 mm/yr (springs) or 3.60 $\pm$4.3 mm/yr (neaps) (Table

7.10.).

It is without doubt that change in tidal levels is positively associated with the change in tidal amplitude and is induced directly by changing sea-level. Within such a well confined estuary, high-tide levels could generally be increased faster than low-tide levels when a tidal wave travels from deep water to shallow water due to geometric convergence, and on reaching the maximum point of tidal amplitude, the rate of the increase in high-tide levels will decrease when the tide moves further upstream, due to the bottom friction being stronger.

The Admiralty Tide Tables (1989) show that high-tide levels rise 1.1 m (MHWST) and 0.7 m (MHWNT) from Southend to London Bridge; after reaching their maximum they fall slightly at Chelsea Bridge; they then rise again further upstream due to the influence of fresh water input. However, low-tide levels fall 0.3 m (MLWST) and 0.1 m (MLWNT) from Southend to London Bridge, and rise obviously beyond. Due to the operation of the Thames Barrier, the future changes in tidal level will be more complicated. Before the operation of the barrier, high-tide levels could reach their maximum at London Bridge. But since the operation of the Barrier, some extremely high levels could only reach Woolwich, such as the surge-high-tide level in 1984 (data from the Thames Water). Without the operation of the Barrier, the present-day process could be maintained into the next century. The relationship between the rise in mean sea-level and high-tide level in the last 40 years has been examined (Bowen, 1972; and this thesis). Providing this relationship unchanged, the rise in high-tide levels will be at the same (or a bit higher) rate as the rise in mean sea-level at Southend, but at London Bridge or Woodwich, a rate of rise in high-tide levels double that in mean sea-level will be likely. For example, a rise of 0.70 m in mean sea-level by the year 2050 may induce an increase in MHWST about 1.40 m at London Bridge.

The velocity at which a progressive tidal wave moves up-estuary depends upon the channel depth (Pethick, 1984) in a one dimensional model, the Thames Estuary for example. The deeper the water, the less bottom friction will be met, so that the faster the tidal stream could run. The deepening in water could also reduce the asymmetry of tidal waves, thus tends to equal the duration and velocity of flood streams and ebb streams.

Future changes in sedimentation

In the Thames Estuary, a rising sea-level means that more suspended sediments will be transported from the outer estuary, especially from the eroded Chalk formation along the north Kent coast, and deposited upstream from the Mud Reaches. Furthermore, the slack water period at high water will become longer due to the reduced asymmetry of the tidal wave, consequently encourage the deposition of fine-grained sediments on the upstream sites in small tributaries, such as the Medway (Kirby, 1990).

Secondly, deepening in sea water could reduce bottom friction, consequently enhance the velocity of flood and ebb streams. As a result of the combination of the enhanced velocity of tidal streams and the restriction of the existing sea embankments to the waterway, the fine-grained sediments on the sea bed within the Estuary, upstream from Tilbury in particular, will become even more unstable and will be more frequently reworked. Thus, the deposition and erosion of the sediments within the Estuary will likely be more active than before. Due to the capital modification of the waterway, the operation of the Thames Barrier, and the improvement of the sea defence system, the future rise in sea level will complicate the sedimentary process in the Thames Estuary. More detail investigations are needed.

Retreating of saltmarshes

As suggested by Kirby (1990), a rising sea-level could erode the saltmarsh cliffs. If sea level rises as scenario 1 during the next century, the covering area of the existing saltmarshes will be reduced gradually while the surface level of the saltmarshes will be elevated. If sea level rises as scenario 2, however, the existing saltmarshes will disappear totally from the Estuary by the year 2050.

7.4. Discussion

It was suggested that a 0.30 m rise in sea level could double the occurrence frequency of storm surges of a same height in the southern North Sea (Rossiter, 1962a). Coker et al. (1989) indicated that, for the surge seasons

1972/3 to 1988/9, the danger levels for coastal inundation for some locations on the east coast were equalled or exceeded on 112 occasions. A rise of mean sea level of only 0.20 m would increase the number of these danger warnings by a further 334. They also indicated that large surge events (in excess of 0.6 m) were responsible for 22 danger level warnings for the seasons analyzed, but if mean sea level were increased by only 0.5 m the danger level would be equalled or exceeded on 146 additional occasions.

However, one should bear in mind that a storm surge is generated commonly from a depression in air pressure. In other words, the occurrence of storm surges would be dependent on meterological conditions. A rising sea-level should not be a direct factor to the increase in storminess. However, changes in climate could alter the meterological conditions. It was indicated that the frequent occurrence of severe storms during the transitional period from a cold to a warm epoch (900-1000 A.D.) or from a warm to a cold epoch (1300-1400 A.D.) was explained as a result of an enhanced thermal gradient between latitudes 50^0 and 65^0 (Lamb, 1984). From this point of view, the global warming could increase the frequency in storminess. This information, however, is apparently not sufficient to quantify the future frequency of storminess. Again, changes in wind stress and precipitation are not clear, and therefore more studies in these aspects are needed. In terms of coastal response to the changing sea-level, sediment supply is an extremely important factor. This factor associated with hydrological factors would be the key to quantify the sedimentation and erosion in coastal areas.

Nevertheless, the future rises in sea level would likely to alter the existing tidal regimes and sedimentary processes, and the nature of coastlines and saltmarshes. If sea level rises at a high rate as Scenario 2, the consequence will be more severe. In summary, the natural responses to the rising sea-level are concluded as follows.

1990-2050

Case 1. sea-level rises at a low rate as Scenario 1:

Tidal regimes within Morecambe Bay and the Thames Estuary will be the same as those in the past 50 years, but the high tide levels will be continuously raised at the same rate of the rising mean sea-level in Morecambe Bay and at Southend, the lower Thames Estuary, and at a doubled rate in the upstream around London Bridge. Due to the tidal regime being not changed, the pattern of sedimentation will change little. In Morecambe Bay, the intertidal sand-banks will continue their movement seawards as they used to do during the past century (Pringle, 1987), at first narrowing the existing tidal channels and consequently shallowing them. The main tidal channels will keep their meandering in the lower reaches of the river estuaries, resulting in erosion at the seaward edge of saltmarshes. Whilst, the accretion on the surface of saltmarshes could keep pace with the rising sea-level. In the Thames Estuary, the maximum accumulation of suspended sediment will be maintained around the Mud Reaches, as it used to be in the past 50 years, and capital dredging will still be necessary to keep the navigational waterway open. The existing saltmarshes in the lower Thames will keep growing and not be eroded completely. In both areas studied, sea embankments will not be under threat of erosion, although by the end of the period erosion on the seaward front of sea embankments would occur.

Case 2. sea-level rises at a high rate as Scenario 2:

At first, the tidal range may be remarkably enhanced in the Thames Estuary, consequently the high-tide levels will be raised faster than that of mean sea-level. The velocity of ebb-tide flows will also be increased. In Morecambe Bay however, the tidal range will be slightly reduced particularly in its northern and southeastern parts, because the high-tide levels may rise more slowly than the low-tide levels due to more supertidal areas being inundated. Within both areas studied, these changes seem not to be uniform from place to place. In Morecambe Bay, for instance, the tidal range might be enhanced in the central and southwest parts of the Bay. In the Thames, high tide levels will rise much faster in the upper reaches from Woolwich than in the lower reaches. It is clear that such changes in intertidal hydrological conditions may consequently alter the present sedimentation. The consequences in Morecambe Bay seem to include that: more fine-grained sediments will be transported and deposited in the heads of the main estuaries; tidal channels become more straight and less meandering due to the stronger tidal currents; sediments on sand beaches will become coarser or with more shingle because of the deeper water and the stronger wave climate; the zones of saltmarshes are likely to retreat, and the new saltings will grow upon the former mature marshes. In the Thames, sediments on the intertidal flats will become more unstable and will be more frequently recycled. The depositional maximum of suspended sediment will be moved slightly upstream from the Mud Reaches.

2050-2100

Case 3. sea-level rises as Scenario 1:

The natural responses would similar to those described in Case 2.

Case 4. sea-level rises as Scenario 2:

High water levels will increase dramatically in the Thames and Morecambe Bay. Velocities of tidal currents will increase and sea-bed morphological features in Morecambe Bay and the Thames may be modified considerably. The sediments on the lower intertidal zone would be eroded and deposited onto the upper intertidal zone. As a result, very little saltmarshes could survive and most of them will be overlaid by clastic sediments. The seaward front of most sea embankments will face direct wave attacks, particularly during storms.

Physical impacts of the projected sea-level rise on the lowlands behind the embankments are discussed in the next chapter.

CHAPTER VIII

COASTAL LOWLANDS AT RISK OF MARINE INUNDATION

8.1. Introduction

Impacts of future sea-level rise on the lowlying areas beyond sea defences or the present tidal limit seem to be completely different to those on the intertidal zone. This is because human activities have been intensified on the coastal areas around Morecambe Bay and along the Thames Estuary for over 1000 years since the Roman times (Fitter, 1945; Sinclair, 1964; Freeman, Rodgers and Kinvig, 1966). Some of these human activities, building embankments along the water front for example, have considerably altered and affected the natural process of the coastal areas.

This Chapter attempts to analyze the likely impacts of the projected sea-level rise on such lowlands currently protected by sea defences. There seem to be two major sorts of impacts: 'permanent' marine inundation and 'occasional' damage from extremely high tides and surges if natural and artificial sea defences fail to protect these lands.

In the following sections therefore, assessments are carried out to the background of the two coastal lowland areas, the existing sea defences, zoning of the lowlying lands subject to long-term potential inundation and short-term storm-surge and flooding damage, and the landuse pattern on these lands.

8.2. Relevant Background

Before analyzing the likely impacts of sea-level rise on the coastal lowlands, historical records need to be reviewed. The projected high-tide levels for the two areas studied and the interaction of tides and surges in these areas are discussed. Finally, the principle of flood-hazard land zoning is illustrated.

8.2.1. History of sea flooding

Heights of abnormally high tides in Morecambe Bay during the last century were recorded instrumentally (Lennon, 1963; Graff, 1981), but only the recent evidence of the high-tide induced sea flooding has been well documented (NWW, 1983). It was reported (NWW, 1983) for example that the most serious of recent incidents occurred in November 1977, when some 7,100 acres (2870 ha.) of valuable agricultural lands, isolated farms and upwards of 70 properties in the village of Pilling were affected by flood water. The livestock mortality was high, field drainage was badly affected and in all some £750,000 of damage was sustained (NWW, 1983). This event carried sea level to 6.6 m O.D. at Heysham (data from the Proudman Oceanographic Laboratory) and 7.5 m O.D. at Preston some 40 km south of Morecambe Bay (Tooley, 1989). The level of 6.6 m O.D. in southern Morecambe Bay was estimated to be reached once in 100 years (Graff, 1981). In order to protect the lands from a recurrence of this level, the sea defence along the south coast of Morecambe Bay were raised to a level of 7.6 m O.D. during the 1980s (NWW, 1983).

More recently, in Towyn, the town and the adjacent areas were flooded as a result of a breaching of the sea wall on 26 February 1990. Towyn was inundated within minutes, and water quickly flowed south and then spread east to Kinmel Bay and west to Pensarn. In the town centre, a flood mark has been surveyed to an altitude of 5.39 m O.D. This event not only caused flooding but also extensive erosion of the coastline (Englefield et al., 1990).

Based on the records from the tide gauge at Heysham Head provided by the Proudman Oceanographic Laboratory, abnormally high water levels over 6.0 m O.D. have occurred at Heysham at least 15 occasions for the last 50 years. For the 19th century, strong S.W. winds might raise the actual high tide level well above the predicted height, the highest recorded storm tide reaching 7.6 m O.D. on 8 October 1896 (Gray and Scott, 1987).

In the Thames Estuary, an event of sea flooding was recorded as far back as 1099 in the Anglo-Saxon Chronicle (Gilbert and Horner, 1984). However, the first description of the sea flooding was made by Stow (see Gilbert and Horner, 1984). In his 'Chronicles of England', he wrote that, in the year 1236 the River Thames, overflowing its banks, caused the marshes all about Woolwich to be all a sea wherein boats and other vessels were carried by the stream, so that besides cattle a great number of inhabitants there drowned, and in the great Palace of Westminster men did row with wherries in the midwest of the Hall. Moreover in the year 1242, the Thames, overflowing the banks about Lamberhithe, drowned houses and fields by the space of six miles, so that in the Great Hall at Westminster men took their horses, because the water ran overall.

In the 19th century there was a series of London floods (Brooks and Glasspoole, 1928), for example those in 1834, 1852, 1874, 1874 and 1881 (Gilbert and Horner, 1984). The record high level set by 1881 was not exceeded until 1928, when a high surge combined with a high flow over Teddington Weir exceeded the 1881 level by a foot (30 cm) (Gilbert and Horner, 1984). This latter event has seriously affected London. The Times (8-11/1/1928) described that on January 7, 1928 the flood area included the half square mile around the Tate Gallery, South Bank around St. Thomas' Hospital, the Tower of London, Bankside, Billingsgate, Teddington Lock to Hammersmith Bridge and 20 acres of Battersea and Wandsworth. During the flood, at least twenty-four people were killed; Houses were severely damaged in Westminster where 451 houses were flooded and a further 270 houses suffered a backflow from drains; Large crowds had to be kept away from the Embankment; and Local governing bodies were offered short term loans by the Ministry of Health for repair works (The Times, 8-11/1/1928).

The 1928 level at London Bridge was exceeded in 1953 by a surge tide nine inches higher (Gilbert and Horner, 1984). Much damage and flooding occurred downstream and the sea poured over the embankments and flooded extensive areas of reclaimed land to a depth of from 1 to 2 ft (Robinson, 1953). In Canvey Island for instance, 40 breaches varying in width from 10 to 200 ft were made in the sea defences (Robinson, 1953). During the same event, two breaches of 700 and 800 yards respectively were made in the northern sea wall to the Wantsum Channel, east Kent, so that the railway there was put out action for four months (Coleman and Lukehurst, 1967).

There was little doubt that the risk in sea flooding would increase as ground altitudes continue to decline, in which two sets of processes were involved: firstly the dewatering of sediments, oxidation of organic soils and their consolidation; and secondly, subsidence as a result of isostatic adjustments (Tooley, 1989). The second set of processes will not occur in Morecambe Bay, in where there is slight uplift instead (Shennan, 1989).

Under the circumstances of a rising sea-level at a rate of the scenarios given in Table 6.3. and 6.5., the coastal lowlands of Morecambe Bay and the Thames Estuary would have more floodings than they had in the past. In the next century, they seem to be at much greater risk of sea flooding, i.e. from extreme tidal events and storm surges.

8.2.2. Projected future high-tide levels

The likely sea-level rise in the next century has been summarised as two scenarios in Chapter VI for the two areas studied. The local uplift or subsidence factors have been considered during estimation of the rates of future sea-level rise. In Chapter VI, it is assumed that the rates of rising in mean sea-level would be the same as Hoffman suggested (1984). According to the discussion in Chapter VII, a rising sea-level could raise both high-tide and low-tide levels. On the Thames, high-tide levels are likely to rise faster than the mean sea-level. Whilst high-tide levels would rise slightly slower than the mean sea-level in the northern and southeastern parts of Morecambe Bay. Considering the variation in high-tide levels within Morecambe Bay, and between downstream and upstream sites in the Thames, the two scenarios for the high-tide levels (HAT and MHWST) for the two areas are calculated. Here based on the analysis in Chapter VII, the rising rate of high-tide levels at London Bridge is assumed to be 1.65 times higher than that at Southend. It is also assumed that the rising rate of high-tide levels is slightly higher in the southwest part than the north and southeast part of Morecambe Bay but the difference would be very small. For the next century in Morecambe Bay, it is expected that the levels of MHWST and HAT at its northern part would be 0.40 m higher, and at the southwestern part 0.30 m lower, than those at Heysham, as they are at the present day. The results of the calculation are listed in Table 8.1.

Table 8.1. High-tide levels (m O.D.) for the two Scenarios

	MHWST		HAT	
Morecambe Bay:	2050	2100	2050	2100
Heysham				
Scenario 1	4.80	5.13	5.90	6.23
Scenario 2	5.06	6.16	6.16	7.26
The Thames Estuary:	MHWST		HAT	
	2050	2100	2050	2100
Southend				
Scenario 1	3.23	3.68	3.93	4.38
Scenario 2	3.49	4.70	4.19	5.40
London Bridge				
Scenario 1	4.61	5.35	5.59	6.33
Scenario 2	5.05	7.03	6.03	8.00

8.2.3. Interaction of tides and storm surges

Interaction of tides and surges is another important hydrological phenomena in the North Sea and the Irish Sea. Storm surges represent one of the most menacing natural disasters that threaten the British Isles. In practice, a coastal flood seems to be a result of a combination of meteorological and hydrological events, such as that a surge induced by a depression and wind stress is amplified by a high tide. In order to determine the sea defence level and find out the way to forecast the damaging floods as earlier and accurately as possible, mathematical analyses of one dimensional model for the Thames Estuary (Rossiter, 1962a; Prandle and Wolf, 1978; Wolf, 1981) and two dimensional model for the southern North Sea (Banks, 1974; Prandle, 1975) were carried out for investigating the interaction of surges and tides.

Interaction between tides and surges is very strong in the Thames because of the shallow water there (Wolf, 1981). Interaction increases with distance travelled up the Thames, and such increases were consistent with the larger range of tides, the shallower water and the convergence of the estuary (Bank, 1974). Surge levels are, in general, amplified progressively as surges propagate southwards in the North Sea, and on reaching the Thames, the surge peaks tend to occur on the rising tide (Prandle and Wolf, 1978). For any surge event, maximum surge levels would generally occur at high tide. The significant feature of the storms, which occurred in 5-8 January 1928 and 9-10 December 1965 for examples, was that they travelled rapidly across the North Sea approximately during the time between the preceding tidal high water and the high water on which the surge peak occurred in the Thames (Prandle and Wolf, 1978).

In contrast, wind-induced surges do not always coincide with high tides. As Banks (1974) described, (1) for equal sequences of meteorological conditions, wind-induced surge peaks occurring near to the time of tidal high water are decreased and the presence of the peaks occurring on the rising tide are increased. (2) Wind-induced surges rising to a maximum some time before high tides and then remaining fairly constant until after tidal high water are, in the presence of the tide, transformed to have two peaks, one occurring before and one after tidal high water. Prandle (1975) also explained that a feature of the wind-surge component was its rate of change: at Southend a change of 0.7 m/hour is shown; this response was probably even more rapid in localized shallow areas. He further indicated that the surge levels in the Thames might include a large component due to the wind stress acting over the southern North Sea. However, Prandle (1975) summarised, on the basis of his two dimensional model simulating the disastrous surge of January-February 1953, that the external surge along the northern boundary is the largest component. It travels along the east coast of England essentially unchanged in size and shape, with a maximum amplitude of approximately 2.3 m. The wind stress represents the second largest component, with a maximum amplitude of approximately 1.3 m along the east coast of England.

Dugdale (1990) reported that the North Sea has experienced, on average, five surges each year with magnitudes up to 1 m. However, the theoretical maximum surge is close to 4 m. In fact, during the infamous 1953 storm surge in the North Sea, predicted sea levels were exceeded by up to 3 m along the south-east coast of Britain (Tooley, 1989; Dugdale, 1990). At Pilling on the south side of Morecambe Bay, the storm surge in November 1977 added 1.7 m to predicted levels (Tooley, 1989), and again in 1982.

8.2.4. Resolution of ground data

The coastal lowlands around Morecambe Bay below the 10 m contour and those adjacent to the Thames Estuary below the 5 m contour are defined as the lowlying coastal lands. The selection of these contours is due to the availability of altitudinal data. The areas below 10 metres in Morecambe Bay will lie close to the projected HAT in the next century (Table 8.1.) and the areas around 5 metres along the Thames Estuary will lie below the projected HAT. These areas are therefore likely to be inundated by sea water and by back up of fresh water (Whittle, 1990) as sea level reaches the altitudes of the

Scenario 1 or 2 (Table 8.1.) during the next century.

The contour lines on the two lowland areas have been digitized from O.S. maps, as a database. During the current study, databases in two scales have been established: the low resolution databases digitized from 1:25,000 O.S. maps, and the high resolution databases converted from spot heights in a SUN computer using UNIRAS software. In the latter case, spot height data were collected from the unpublished 1:2,500 O.S. maps at the Ordnance Survey, Southampton.

In the low resolution databases, the one of Morecambe Bay comprises 14 sheets of O.S. map (Table 3.2.), and the Thames, 20 sheets (Table 3.3.). It must be indicated that there is mix of metric conversions at the present O.S. maps: most editions covering the areas studied are metric and display the +5 m, +10 m and +15 m O.D. contour lines, whereas other sheets show imperial value contours converted to metric with +8 m and +15 m contour lines. Hence, matching the +5 m and +10 m contour lines on continuous sheets between a real metric one and an imperial metric one is not possible. In this case, the +5 and +10 m contour lines are interpreted from the imperial metric sheets by adding spot heights which are collected from the 1:2,500 maps in the Ordnance Survey, Southampton.

In fact, the sea-level rise scenarios demand higher resolution altitudinal data, than are published by the Ordnance Survey. For instance, contours with 1 m intervals are required. Without these high resolution altitudinal data only a general assessment can be made about the impacts of sea-level rise scenarios.

Therefore, an attempt to establish such high resolution databases has been made during the current study. Due to the availability of data sources and the time limitation, only two high resolution databases are set up to cover the areas: 1. Heysham and Morecambe in Morecambe Bay; and 2. Canvey Island and the adjacent areas on the Thames Estuary. Contour lines with 1 m or even 0.5 m intervals can be interpreted and generated from these computerised databases (Fig. 9.6).

The major uncertainty with these altitudinal databases could comes from the changes in ground level since the production of the maps. The ground altitudes of these maps were levelled in 1957-1963. Since then, however, ground altitudes in some places have significantly declined due to consolidation and compaction of the sediments underneath. The levelling from a bench mark at High Frith to the Deanholme Moss, Skelwith Pool at northern Morecambe Bay, suggests that the ground level has declined by nearly 0.7 metre, as a result of the drainage since 1970s. A relevelling to the same place (Nijhof and Tooley, 1990) indicates that the range of values of ground altitude reductions in the past 11 years following drainage is from 1.6 to 0.6 m or 145 mm/yr to 54 mm/yr. Unfortunately, for the lowlands of both areas studied as a whole, this sort of change, as well as other likely changes in ground altitude, have not been able to quantify yet, so that they are not included into the currently established databases.

8.2.5. Principle of the flood-hazard land zoning

In order to assess the impacts of the likely breaching of the sea embankments, in this section, a zoning of the likely flood-hazard lands (Hoyt and Langbein, 1955) is carried out by using the GIS technique. Such zoning is to work out which coastal lowlands will be inundated, how extensive such lowlands will be and what type the existing landuse is. The zoning of flood-hazard lands should include identifying details of the likely hazards and degree of the risks, which will be discussed in Chapter IX. The results of such zoning could form a base of evidence for policy makers and lowland communities to make their decision: whether it is worth to invest and raise the heights of the embankment.

The flood-hazard land zoning, as a general policy in the responsibilities of the central and local authorities for flood protection, is likely to slow development on the lowlands. However, so large a part of the coastal lowlands is already in use, and there are high possibilities of obtaining governmental funds for flood protection. The reasons of growing use of coastal lowlands reflect the real and seeming advantages: the coastal lowlands are flat, material supplies are close at hand, waste disposal may be easy, and the most important, the lands are relatively cheap. Present policy leads to a vicious circle: the greater development of the coastal lowlands, the greater the benefits that can be shown for flood protection. An increasing level of protection from sea flooding by raising sea embankments could encourage further crowding and developing on the protected lands. Thus more properties and new remodelling would occur, as the experience in the Thames lowlands during the past decades for example. Afterwards, with an extreme flood that would exceed the capabilities of the protection system, the losses of property and life would be greater than even before.

Under the circumstance of a rising sea-level, the governing authorities, financial organisations and the lowland communities should make their considerations and decisions about their properties already on the lowlands and their further investments. On the other hand, insurance companies should think about their insurance policies in order to meet the foreseeable loss from sea flooding. In fact, the coastal lowlands, such as the Thames lowlands, has already been used intensively with very high commercial values, and a further development is likely. Such zoning should, therefore, carry a powerful economic message and provide necessary advice to the lowland communities.

The first step of flood-hazard land zoning in the current study is to recognize the flood-hazard wherever it may exist, and work out what type of commercial use has already been developed on the confined coastal lowlands. Economic assessment of the likely flooding is not made since it is away from the main gaol of this thesis. The results illustrated in the following sections may however provide ideas of how much lands within the two areas studied would be 'permanently' lost if there is no further high level protection, i.e. the lowland communities would give up the lands and move further inland.

The second step of the zoning is to identify the likely damages of a sea flooding on the lands, properties and communities. This assessment is carried out in Chapter IX, including investigation of the three pilot areas and recognition of the likely flood hazards which could happen if the lowland communities tend to stay in the areas.

During operating the zoning on the both areas studied, the altitudinal and landuse databases were digitized from 1:25,000 O.S. maps, and the 1981 population census databases were applied.

8.3. The Coastal Lowlands around Morecambe Bay

8.3.1. Altitude of the coastal lowlands

At present, the ground level of many places around Morecambe Bay are close to the local MHWST level, for example the Pilling area and the lowland behind Heysham-Morecambe in Morecambe Bay. If sea level rises as the Scenario 2, even more places would be flooded by high tides, providing no protection by means of sea defences.

By considering the altitude of the coastal lowlands and the present and projected future high water levels (Table 8.1.), the lands at greatest risk are identified as those lying below the 10 m O.D. contour in Morecambe Bay. To this outline has been added the 15 m contour in order to establish the extent of the 'buffer zone'. This buffer zone may be affected during extreme conditions and by backing up of fresh water. Under this definition, the coastal lowlands around Morecambe Bay are outlined in Figure 8.1.

In Morecambe Bay, the areas below 10 m contour cover 346.3 km^2 (34630 ha), in which the areas below 5 m contour cover 124.6 km^2 (12460 ha) mainly lying at Pilling, Heysham-Morecambe, and the Kent valley. The areas between 5 and 10 m contours occupy 221.7 km^2. These lowlands were built up mainly by Flandrian unconsolidated sediment, such as intertidal clastic and organic deposits. The ground altitude across these lowlands varies between about 4.5 to 9.0 m O.D. Most of the mature marshes and sheep pastures are below 6 m O.D., whilst the raised bogs and mosses are around 6-9 m O.D. The areas higher than these levels are mainly rocky hills of Carboniferous and Permo-Triassic ages.

Comparing the altitude of the coastal lowlands with the scenarios in Table 8.1., it is suggested that frequent inundation on these land could happen in the next century, provided no protection of sea defences on the coasts. However, sea embankments have already been built on most of the coasts in Morecambe Bay (see section 7.2.). The remaining questions include: Are the existing sea embankments high enough to protect the lowlands if sea level rises as the Scenario 1 and 2; Until when the current defence levels should be raised; and How much the defence levels should be raised.

8.3.2. Lands and residents at risk

The landuse type on the lowlands between MHW mark and the 10 m contour is interpreted from the 1:25,000 O.S. maps and classified into four major types, agricultural land, industrial estate and urban-residential area. These landuse types were digitized into a Geographical Information System and are displayed in Figure 8.2. The area of these landuse types, except for the communicational networks, are calculated by the GIS and listed in Table 8.2.

Table 8.2. Types of landuse in Morecambe Bay lowlands

Morecambe Bay	below 5 m (km^2)	(ha.)	below 10 m (km^2)	(ha.)
Agricultural	73.5	7350	253.4	25340
Industrial	0.3	30	9.2	920
Urban & Residential	10.8	1080	31.3	3130
Open land	0.3	30	5.2	520
Saltmarshes	39.7	3970	47.4	4740
Total	124.6	12460	346.5	34650

Classification of agricultural lands
(including open lands and part of saltmarshes)

	below 5 m (km^2)	(ha)	below 10 m (km^2)	(ha)
Grade 2	12.4	1240	59.8	5980
Grade 3	68.6	6860	148.1	14810
Grade 4	16.0	1600	31.9	3190
Grade 5	7.5	750	13.6	1360
Total	104.5	10450	253.4	25340

Industrial estates

	below 5 m (km^2)	below 10 m (km^2)
Factories	0.2	8.1
Nuclear Power	0.0	0.9
Sewage works	0.1	0.2
Total Industrial estates	0.3	9.2

Agricultural lands

The majority of the lowlands around Morecambe Bay is used for agricultural purposes, such as for the famous sheep and beef production, and forests (data from the Second Land Utilisation Survey of Britain). These agricultural lands cover 253.4 km^2 (25340 ha), about 73.14 percent of the total coastal lowlands below 10 m contour, calculated from 1:25,000 O.S. maps (Fig. 8.2.), in which, the agricultural lands below 5 m contour occupy 104.5 km^2 (10450 ha). These lands were classified as Grades 2-5 by the Ministry of Agriculture, Fisheries and Food (MAFF) (Fig. 8.3.). The Grade 2 agricultural lands occupy only 59.8 km^2 (5980 ha), lying on the south shore of the Bay, with high productivity in crops, cattle and livestock, but under great risk of sea water inundation. The Grade 3 agricultural lands are the dominant and cover 148.1 km^2 (14810 ha), about 58.4 per cent of the total agricultural land below 10 m contour in Morecambe Bay. The Grade 3 lands are mainly used for cattle. The Grades 4 and 5 only cover 31.9 and 13.6 km^2 respectively. Most of the Grade 5 lands are currently the unused saltmarshes and saltings, which would hardly be reclaimed to be agricultural lands if they are frequently inundated as sea level rises.

Industrial estates

In Morecambe Bay, only a few factories and plants were installed in the lowlands below the 5 m and 10 m contours (Fig. 8.2.), besides the harbour facilities. However, there is a nuclear power station on the water front at Heysham. There is a potential consequence of releasing the nuclear radiative material if the power station is damaged by a marine flood or wave attack. This sort of damage is more likely during the second half of the next century as sea level rises at a rate of the Scenario 2.

An assessment to the likely damages of the industrial installation from a flood is made in section 9.3. The area around Heysham and Morecambe, as a pilot area, is investigated in detail.

Urban and residential areas

In Morecambe Bay, the major urban areas below 10 m O.D. cover 31.3 km^2, with areas about 10.8 km^2 below the 5 m contour (Fig. 8.2.). They locate mainly in Fleetwood, Morecambe, and Barrow. Within these areas, there are properties such as houses, shops and buildings for commercial uses; social service facilities including hospitals, schools, libraries, and offices of local authorities; communication facilities, like post offices and traffic networks; and electricity and water supply facilities. It would be possible to identify sectors in urban areas in the near future. The number, value, and type of these properties, integrated with the altitudinal data within the GIS and the scenarios of sea-level rise, may form the foundation, from which an assessment on the economical process to the rising sea-level can be made.

Coastal residents

The digital ward boundaries (within GIMMS) is integrated with census data (the population census, 1981). Around Morecambe Bay, there are wards which are totally or partly below the 10 m contour and may be affected during a flood. There are 13,420 persons living in 22 wards which are totally below 10 m contour. The other 22,124 persons are living within 58 wards which are partly below 10 m O.D. The distribution and densities (person per square km) of the population living in the coastal lowlands around Morecambe Bay are shown in Figures 8.4. and 8.5.

From the census data, over 35 thousand people living in the Morecambe Bay lowlands would be directly and indirectly affected by future sea floodings. Furthermore, in the rural wards, farmers and their families tend to settle in individual farms. Figure 8.6. shows the farm houses which lie on the lowlands. These farms would be isolated by sea water if a flood occurs. Evacuation of these farmers and families would be very difficult. A special warning system for these farms is necessary.

Communication networks

It is clear that sea water inundation could also damage the communication networks. Temporary inundation by high tides could interrupt the transportation, which in fact used to happen at the road A588 across Pilling Marsh, on the south shore of Morecambe Bay, before the new Pilling embankment was constructed. This sort of evidence is currently happening at the road from Burgh-by-Sands to Drumburgh on the south coast of Solway Firth.

The communication networks below 10 or 5 m O.D. are likely to be inundated more frequently as sea-level rises over 1 or 2 m during the next century. As a result of frequent floodings, the quality of these road networks will become poor. On the other hand, floodings could also damage traffic facilities and interrupt the escape routes for the lowland residents.

Figure 8.7. shows the networks on the Morecambe Bay lowlands, suggesting sections of the road networks are at great risk of marine inundation. Road sections accessing Fleetwood and crossing the Pilling area, and the road crossing the Kent valley will be most vulnerable. The railway along the north shore of the Bay will also be under threat.

8.3.3. Embankments in Morecambe Bay

Sea embankments have been built since the coastal marshlands were reclaimed by the local people (Freeman, Rodgers and Kinvig, 1966; Robinson, 1987). The existing embankments along the water front around the Bay comprise three major types: concrete sea defences, sea walls associated with a railway, and sand-filled embankments. The first type of sea embankments were only built in front of urban areas and industrial estates, such as those in Fleetwood, Knott End-on-Sea (Photo 6), Heysham and Morecambe, and Barrow. The second sort of sea defences were built during the development of the Furness steel works about some 200 year ago (Robinson, 1987), and several sections of a railway were built on the marshlands at the east and north coasts of the Bay. The third, the sand-filled embankments are the majority of the sea defence system commonly in the north, east and south coasts of the Bay (Photo 3). The first and second types of sea defence were maintained in good condition, however, the third one is still in very poor condition and lacks improvement, except for the one at Pilling. The total length of the sea defences in Morecambe Bay is calculated from the 1:25,000 O.S. maps, being 34.8 km in length of the first and second types of sea defence, and 92.7 km, the third type.

The crest of the existing embankments reaches an altitude from about 6.5 to 7.0 m O.D. (data from National Rivers Authority). For example, the current crest of a sand-filled embankment in front of Skelwith Pool is at 6.72 m O.D. (measured by the current study). Some of the sea embankments have, however, been raised during the last decade. In Pilling Marsh, the south coast of the Bay for example, as a result of the deficiencies in the old defences, breaching and over-topping had been taken place on a number of occasions, a new soil-filled embankment of 7.5 km in length was constructed after the severe flooding of November 1977 (NWW, 1983). The crest level of the new embankment is uniform at 7.62 m O.D., providing 0.76 m above the level associated with the November 1977 surge (Fig. 8.8.). Sheltered sections of the seaward face are provided with a reinforced turf cover, while over the exposed lengths conventional stone mattress armouring has been installed in order to give a greater degree of wave protection. The costs for constructing such embankments of 7.5 km in length are in total up to £3,400,000 and the construction was carried out over two years (NWW, 1983).

In order to meet the consequence of future sea-level rise, we must raise and strengthen the existing sea embankments against the rising sea-level, if we want to maintain the current pattern of land-use of the lowlands. In fact, the Lancaster City Council has issued a radical scheme of comprehensive redevelopment at the Central Promenade area (see section 9.3.).

On the basis of the scenarios of sea-level rise in Table 8.1., an assessment should be made to determine the heights at which the existing sea embankments should be raised and the time when improvement for these sea embankments have to be made. Providing that sea-level rises as Scenario 1 (Table 8.1.), most of the coastal embankments around Morecambe Bay would still be sufficiently high to prevent normal high-tide levels (i.e. the HAT and MHWST, Fig. 8.8.) during the next century. However, if sea level rises as Scenario 2, the HAT (about 7.26 m O.D. at A.D. 2100) could breach most of the old embankments and threaten the new embankments before the end of the next century (Fig. 8.8.).

If a 1.7 m extra height from a storm surge once in 100 years (NWW, 1983; Tooley, 1989) or somewhat once in 50 years (see Table 7.3. and Graff, 1981) being added upon a high tide, the flood level could reach at 7.0 m O.D. (Scenario 1) or 7.3 m O.D. (Scenario 2) at Heysham (Fig. 8.8.), starting at the year 2030. It means that most of the existing sea embankments may be breached or under threat of serious erosion.

It is therefore suggested that (1) during the first half of the next century, the existing sea embankments along the coasts of Morecambe Bay would meet much more frequent and damaging attack from sea waves, particularly if sea level rises as Scenario 2; (2) by the year around 2050, most of the sea embankments will be insufficiently high to protect the land from sea floodings, therefore improvement for these embankments should be carried out before the year 2050; (3) in order to prevent sea flooding beyond the year 2050, the embankments in the south coast of the Bay should be raised up to over 8.0 m O.D. and those in the north coast, 8.7 m O.D.

8.4. Coastal Lowlands at Risk in the Thames Estuary

8.4.1. Altitude of the coastal lowlands

At present, the ground level of many places along the Thames Estuary are lower than or close to the local MHWST level, in Canvey Island and Isle of Sheppey in particular. If sea level rises as the Scenario 2, even more places would be flooded by high tides, providing no protection by sea defences.

By considering the altitude of the coastal lowlands and the present and projected future high water levels (Table 8.1.), the lands at greatest risk are identified as those lying below the 5 m O.D. contour. To this outline has been added the 10 m contour for the Thames Estuary in order to establish the extent of the 'buffer zone'. This buffer zone may be affected during extreme conditions and by backing up of fresh water. Under this definition, the coastal lowlands in the Thames Estuary are outlined in Figure 8.9.

In the Thames Estuary, the areas below the 5 m contour cover 513.6 km^2 (51360 ha), which are the Flandrian alluvial plains (Devoy, 1979). The areas between 5 and 10 m contours lie mainly on the late Pleistonce terraces (Devoy, 1979) and cover 291.1 km^2. Thus the total lowlands below 10 m O.D. occupy 804.7 km^2 (80470 ha). The ground level of the lowest part of the lowlands increases gradually from 2 m to 6 m O.D. upstream from Southend to Teddington. In which, the lowlands around Canvey Island and the Isle of Sheppey are at about 2 m O.D.; the areas between Tilbury and Woolwich, about 3-4 m O.D.; central London, especially the south bank , about 4-5 m O.D.; beyond the Richmond Lock, 5-6 m O.D. The lowest spot height, 0.9 m O.D., is found in Canvey Island and Foulness Island.

8.4.2. Lands, properties and lives at risk

The landuse type on the lowlands between MHW mark and 5 m contour or 10 m contour is interpreted from the 1:25,000 O.S. maps and classified into four major types: agricultural land, industrial estate, urban-residential area and saltmarsh. These landuse types were digitized into a Geographical Information System and are displayed in Figure 8.10. The area of these landuse types, except for the communicational networks, are calculated by the GIS and listed in Table 8.3.

Table 8.3. Types of landuse in the Thames lowlands

Thames Estuary	below 5 m (km^2)	(ha.)	below 10 m (km^2)	(ha.)
Agricultural	331.2	33120	445.3	44530
Industrial	49.9	4990	67.0	6700
Urban & Residential	84.9	8490	228.7	22870
Open land	23.1	2310	39.6	3960
Saltmarshes	24.5	2450	24.5	2450
Total	513.6	51360	805.1	80510

Classification of agricultural lands (data from MAFF)

	below 5 m (km^2)	(ha)	below 10 m (km^2)	(ha)
Grade 1	23.1	2310	56.8	5680
Grade 2	24.5	2450	38.1	3810
Grade 3	131.1	13110	197.5	19750
Grade 4	127.6	12760	143.7	14370
Grade 5	8.7	870	9.2	920
Total	315.0	31500	445.3	44530

Industrial estates

	below 5 m (km^2)	below 10 m (km^2)
Factories	34.2	50.5
Oil refineries	12.9	13.2
Power stations	1.8	2.2
Sewage works	1.0	1.2
Total Industrial estates	49.9	67.0

Urban areas

	below 5 m (km^2)	below 10 m (km^2)
Urban and residential areas	4.3	193.8
Parks	10.6	27.1
Reservoirs	0.0	7.7
Total	84.9	228.7

Agricultural lands

In the Thames Estuary, the agricultural lands occupy 445.3 km^2, about only 55.33 per cent of the total lowlands below the 10 m contour (Fig. 8.10.), in which the proportion of agricultural lands below 5 m in altitude occupy 315.0 km^2, and dominate the lowlands downstream from Tilbury. These agricultural lands were classified by the MAFF into 5 classes (Fig. 8.11.), ranging from Grade 1 to Grade 5. The areas of these agricultural lands are calculated by the GIS, and listed in Table 8.3. These agricultural lands produce a great value of products for the customers in the Great London and its satellite cities.

Industrial estates

Along the Thames Estuary, there is a great number of industrial estates and complexes already installed within the lowlands subject to flood. The industrial estates located on the lowlands below 5 m and 10 m contours are plotted in Figure. 8.10. These estates include factories, docks, chemical plants, oil refineries, gas storage, power stations, sewage works and other industrial use and service functions (Witherick, 1964; Pailing, 1964; Castle and Stone, 1964; Davis and Baker, 1964). They have been identified from the 1:25,000 O.S. maps, and grouped into four categories: factories, oil refineries, power stations and sewage (Table 8.3.).

Urban and residential areas

In the Thames lowlands, urban areas below 10 m O.D. cover 228.7 km^2, with a area of 84.9 km^2 below the 5 m contour (Table 8.3.). Most of these urban areas concentrate in Central London and its eastern outskirts (Fig. 8.10.). They have experienced considerable damage from flooding by the sea during the last one and two centuries and are currently protected by the Thames Barrier and the associated embankments (Gilbert and Horner, 1984). Beside these, another urban area at high risk is Canvey Island, where the ground level is at only 2 m O.D., i.e. 0.80 m lower than the present local MHWST. Along the river banks upstream from the Thames Barrier, there are not only private and public properties and facilities, but also of most importance, many national offices and archives. On the Thames lowlands, the upper Estuary in particular, houses and urban facilities are extremely expensive and their prices may be about three times those on the Morecambe Bay lowlands.

The International Disaster Institute (IDI, 1981) in London carried out an assessment to the lowlying areas within the Greater London Council and provided a diagram (Fig. 4, in IDI, 1981) showing the areas below 18 ft O.D. (5.50 m O.D.). These areas would be inundated if a flood occurred. The diagram also suggested the areas between 18 ft and 27 ft (5.50 - 8.25 m O.D.) where basements and the Underground would be likely to suffer from back flow of water along sewage pipes, underground ducts carrying pipes and other structural inlets. Buildings within these areas would, in the event of a flood, need to be examined for any structural damage (IDI, 1981).

The damages of sea water inundation on these lowland areas would be more frequent and serious as the rising sea-level is accelerated in the next century. Property maintenances, new housing investments, and new installations in these lowlands and the related insurance policies should therefore be made with careful consideration.

Coastal residents at risk

Residential population in the Thames lowlands is much denser (Figs. 8.12. and 8.13.). There are 1,415,701 persons living in 193 wards which are totally below 10 m contour. The other 938,980 persons are living in 135 wards which are partly below 10 m contour.

Based on the 1971 census, the IDI (1981) indicated that there was a night-time population of 960,000 in the flood risk areas within the Greater London Council. The IDI (1981) also reported that there were over 347,000 households within the flood risk areas, in which over 207,000 dwellings were privately owned. The reinstatement of these private households would depend on the insurance coverage and assets of the owners. Although most of the London inhabitants are settled in the areas above 10 m O.D., there are still a great number in areas below 5 m O.D., such as those in southern Hammersmith, Tower Hamlets, northern Lambeth and Southwark.

It is therefore suggested that about 2.35 million people in the Thames lowlands would be directly or indirectly affected by sea floodings. Furthermore, within the rural wards, farmers and their families tend to settle in individual farms or small villages. Figure 8.14. shows the distribution of the farm houses which lie below 10 m O.D. During a sea flood, those people would be isolated by sea water. The evacuation of them could therefore be even more difficult. A special warning system, the storm tide warning service in east England,for helping these people to escape is necessary.

Communication networks

It is clear that sea water inundation could also damage the communication networks. Figures 8.15. and 8.16. show the communication networks on the Thames Lowlands. Sections of the road networks accessing Canvey Island, Isle of Sheppey, Thames Haven, Tilbury, and the City Airport will be most vulnerable for marine inundation. Railways along both sides of the Estuary will also be at great risk of sea flooding.

8.4.3. Sea defences in the Thames Estuary

Sea defences on the main marsh lands along the Thames were intensively built since the 12th century (Akeroyd, 1972), but the marsh lands on both sides of the mouth of the Thames were not embanked and united until the 17th century (Cracknell, 1959). Up to date, all the lowlying land on the Thames Estuary are fully embanked by either concrete sea defences or soil-filled banks with conventional stone mattress armouring installed on their front slopes in order to give a greater degree of wave protection. The concrete sea defences were built in front of industrial estates, docks, and urban and residential areas (Photos 13-18); whilst the soil embankments, protecting the agricultural land (Photo 12).

The 1:25,000 O.S. maps showed that along the south coasts from Erith to Whitstable, north Kent, there are sea defences of 194.7 km in total length; 70.2 km from Purfleet to Southend on the south Essex coast. Within the Thames Region of the National Rivers Authority, there are flood defences of 193 km in total length along the River Thames from Teddington to Erith and its tributaries (data from the Thames Water).

These sea embankments have been strengthened and raised during this century. For instance, the crest of the embankments in London Bridge has been raised from 5.28 m O.D. of the 1930 defence level to 5.80 m O.D. of the current defence level (Gilbert and Horner, 1984). Since the construction of the Thames Barrier, the flood defence level at Woolwich has been raised to 7.2 m O.D. (data from the Thames Water). In Canvey Island, as many embankments were raised only to 14 ft (4.30 m) O.D. before 1953 (Robinson, 1953), but 17.9 ft (5.45 m) O.D. afterward. The latter height, confirmed by a re-levelling during the current study (see Table 9.1), has been raised again since the 1960s by adding a concrete wall upon the sea embankment (Photos 13-18). Therefore, the current defence level along the south coastline of Canvey Island reaches a height from 6.4 m O.D. (west of the island) to 6.9 m O.D. (east of the island)(see Table 9.1). Up to date, the heights of the embankments from Woolwich upstream towards Teddington Lock increase from 5.6 to 6.1 m O.D.; and from Woolwich downstream towards Canvey Island, 7.2 to 6.4 m O.D. (Fig. 8.17.).

In order to meet the consequence of future sea-level rise, we must raise and strengthen the existing sea embankments against the rising sea-level, if we want to maintain the current pattern of land-use of the lowlands. The Government is planing to promote a linear city east of London stretching for 30 miles along both banks of the Thames (Daily Mail, Monday 19 August

1991). Further east, down-estuary from to the Barrier, six companies are planning to build electricity generating plants (The Independent, Saturday 3 August 1991). On the basis of the scenarios of sea-level rise in Table 8.1., an assessment should be made to the heights at which the existing sea embankments should be raised and the time when such improvements have to be made.

Recently, many scientists and engineers have been concerned about whether the Thames Tidal Barrier is able to protect the lowlands from sea flooding in the coming decades. The engineers of the Thames Water Authority, for example, accepted (New Scientist, 14 July, 1988) that "the £500-million structure needs modifying to cope with the global warming caused by the greenhouse effect, as the world warms, ice melts and sea levels rise." and as a consequence, "the barrier could be breached as early as the middle of the next century." An even earlier breaching of the Barrier by sea water is predicted to happen in 40 years, i.e. around the year 2030, suggested by Dr. Kelly (Daily Telegraph, 26 October, 1989) and by the UEA (the Guardian, 11 October, 1990).

The Thames Barrier and its associated defence system were designed to prevent a high tide of one occurrence in 1000 years (Horner, 1972). The defence level of the Barrier itself was as high as 1.83 m above the 1953 flood level, i.e. around 7.4 m O.D. (Gilbert and Horner, 1964). Although a rising sea-level, a deepening in water depth in the other word, could double the frequency of storm surges (Rossiter, 1962b), a re-occurrence of 1953 surge during the next century is unlikely (Suthon, 1963). However, under the circumstance that mean sea-level rises at a rate of Scenario 2 during the next century, a surge tide of one chance in 100-250 years may be likely to occur (Pugh, 1990). It means that a 2 m extra water level may add upon a high tide (Table 7.8., and Graff, 1981).

In eastern England, the unpublished annual summaries for the surge seasons 1972/3 to 1988/9 indicate that danger levels for coastal inundation for five reference locations on the east coast were equalled or exceeded on 112 occasions (Coker et al., 1989). It suggests that a rise of mean sea-level of only 0.2 m would increase the number of these danger levels by a further 334 occasions (Coker et al., 1989).

On the basis of the current study, a breaching of the Thames Barrier is likely to happen around or later than the year 2050 (Fig. 8.17.), particularly if sea level rises as Scenario 2. Before the year 2050, the Thames Barrier and the associated sea defence system along the Thames Estuary seems to be still effective to prevent sea flooding, providing that sea level rises as Scenario 1 and no surge event (in excess of 2.0 m from a 1/100-250 surge) occurs. Figure 8.17. shows that the MHWST of Scenario 1 plus a 2 m extra height from a surge would not exceed the current defence level.

During the second half of the next century, however, if a extra height of 2 m from a storm surge being added upon the MHWST of Scenario 1, the resulting flood level would be as high as over 5.25 - 5.70 m O.D. at Southend and 6.76 - 7.66 m O.D. at London Bridge (Fig. 8.17.), providing the Barrier is not closed. As a result, the sea defence system, particularly the sections from Tilbury to the Barrier, will be breached. If sea-level rises as Scenario 2, an enhancement of the sea defence system must be carried out as earlier as before the year 2050.

8.5. Summary

On the basis of the above studies, two main points about the likely marine inundation upon the coastal lowlands, Morecambe Bay and the Thames Estuary, can be summarised as follows.

Effectiveness of the existing sea defences

Under the circumstance that sea level will rise at a rate as Scenario 2, most of the existing sea defences on the coasts around Morecambe Bay and along the Thames Estuary would be not effectively sufficient to prevent sea water, and the lowlands being flooded. It is the fact that some sea defences have a relatively high defence level and are designed to surge tides with a long return period, such as the Pilling Sea Embankment (1/100 years) and the Thames Barrier and its associated sea defence (1/1000 years). Due to the rising in sea level and its consequence on increasing frequency in occurrence of abnormally high water levels, those sea defences with high defence levels could also be breached or overtopped before the end of the next century.

The lowlands subject to flood

Coastal lowlands in both areas studied are identified by means of examining their ground altitudes with the sea-level scenarios, employing the technique of Geographical Information Systems. It is indicated that in Morecambe Bay, there are 346.5 km^2 above Mean High Water and below 10 m O.D., of which 124.6 km^2 are below 5 m O.D. In the Thames Estuary, lands below 10 m O.D. and above MHW cover 805.1 km^2, with 513.6 km^2 below 5 m O.D. Most of these lowlands have already been used for different purposes, falling into four major categories: agricultural lands, urban occupation, industrial estates, and unused lands. Once sea water breaching or overtopping the sea defences, these lands would be flooded. If there is no further improvement of the existing sea defences, most of these lands would be inundated more and more frequently, during the second half of the next century in particular. Some of the lands will be permanently lost by the year 2100, if the rise of sea level is continuously accelerated.

CHAPTER IX

LIKELY IMPACTS OF FUTURE SEA-LEVEL RISE IN THE THREE PILOT AREAS

9.1. Introduction

Three pilot areas, Skelwith Pool, Heysham and Morecambe, and Canvey Island, have been investigated for the likely impacts of a rising sea-level. Attention is also drawn to the difference of the three areas, in terms of their landuse types, topographical features, and their implication in regional development. The altitudinal and landuse data were interpreted and digitised from 1:10,000 O.S. maps for Skelwith Pool and Canvey Island, and from 1:25,000 O.S. maps for Heysham and Morecambe. Spot height data were collected from 1:2500 unpublished sheets in the Ordnance Survey, Southampton (Table 3.1.). The spot height data were then applied to establish contour maps for Heysham and Morecambe area and Canvey Island. The sea-level scenarios 1 and 2 (Tables 7.8. and 7.13.) are also applied to the following assessment.

The initial result of a rising sea-level for these areas may be the sea water inundation and flooding. The impacts of such flooding would be very wide, including physical, social and even psychological terms. In this chapter, the direct physical impacts of the flooding is the main concern. Impacts in economic and social terms would also be mentioned.

Indirect impacts from sea flooding on these areas could include loss of confidence in business, loss of payments and profits in trading, and interruption of social services. In other words, the indirect loss could continue.

9.2. Flooding on agricultural land: a case study from Skelwith Pool

Skelwith Pool lies on the east shore of the Leven Estuary, northern Morecambe Bay (Fig. 9.1.). The land on both sides of the tidal inlet, Skelwith Pool, has been built up by alternatively tidal and intertidal minerogenic and organic sediments during the Flandrian (see Chapter IV), and became raised bogs and fens before it was reclaimed by the local inhabitants for agricultural purposes (see section 1.4.1). During the mid-1800s, the fens and part of the raised bogs were cleared and drained, and became sheep pastures (data from the local land drainage book, Holker Estate Office). The remaining raised bogs were not drained until 1970s, but have not been completely reclaimed. These reclamations led the fen and bog formations dewatering, and as a result, the ground level was lowered. For example, the ground surface of the raised bog, the Deanholme Moss, was lowered about 70 cm since the drainage in 1970s (see Section 8.2.4.). The current ground surface of the reclaimed land is around 4.8 - 5.6 m O.D., based on the 1:2500 O.S. maps and the re-levelling data. The landscape of the area is shown in Figure 9.1.

There is a tide gate stopping the sea water at the mouth of the Skelwith Pool. The altitude of the bridge over the tide gate was 6.80 m O.D. (data from the O.S. map, SD 28/38), but was currently raised up about 1 m. In the northwest corner of the land, there is an earth embankment of 1.1 km in length protecting the land from sea water inundation. The maximum height of the embankment crest is 6.90 m O.D. (from the current levelling)(see Fig. 9.2.).

It is therefore suggested that if sea level rises as Scenario 2, sea water would be likely to overtop the embankment and flood the land by the year 2050 during highest astronomical tides. Another likely effect of the rising sea-level seems to be the increasing erosion in the seaward front of the embankment. Thirdly, a rising sea-level could result in enhancement of the ground-water table in the reclaimed land. These three sorts of impacts are discussed as follows.

Sea flooding

A profile of the land surface from landward to seaward (Fig. 9.2B.) is applied to show the relationship with the water levels and effectiveness of the sea embankment. Once sea water overtops the embankment, the pastures along both sides of the Skelwith Pool could be inundated (Fig. 9.1.). Such inundation could likely maintain for only half day if the sea water could be drained away during the coming low tide. Even so, the pastures would still be burned by the sea water, as has happened at Towyn during the February 1990 flood (Englefield et al., 1990).

The damage of the flooding would include that: (1) sea water breaches sea embankment, inundates the land, damages farming facilities and houses, kills growing crops (pasture in this case), livestock and even people; (2) sediment and debris would be dumped upon the agricultural land, and block tidal inlets, outlets, and sewer canals (Li, 1988); (3) sea water may contaminate the soil and ground water by increasing salinity, and bring coastal vegetation communities such as Spartina grasses and reeds up to the drainage canals.

Raising ground-water table

If the sea embankment is improved sufficiently strongly and high enough to prevent sea water to flood, the rising tidal level induced by rising sea-level could still raise up the ground-water table. In other words, the rising sea-level could induce soil waterlogging and complicate the drainage work. The duration and frequency of soil waterlogging critically affects agricultural productivity (Penning-Rowsell et al., 1986; Li, 1988). If the ground-water table is high enough to damage the root systems of the pasture, the production of the land will decline and the cost to lower the ground-water table would be even expensive.

Increasing erosion

Although the surface of saltmarshes could accrete as sea level rises, erosion on the edges of the saltmarshes would become severe. Once the saltmarshes are eroded away or become very narrow, erosion could in turn happen to the earth embankment. Therefore, armouring the seaward front of the embankment will be required.

However, in this particular site, erosion may not become severe. It is because: 1. the site closes to the head of the estuary, and is relatively sheltered; 2. a rising sea-level may bring more fine-grained sediments to there; 3. if sediment supply is sufficiently high, the surface of the saltmarshes would be raised far enough up or overlaid by clastic sediments, as a result, erosion would not occur. It must be indicated that such erosion could happen in other coasts, where sediment supply is not sufficiently high.

Based on the above assessment, it is suggested that the similar impacts would be likely to happen at the valley of the River Kent, Pilling Moss, and the lowlying agricultural lands on the lower Thames. In short, if one would protect the land from sea flooding during the next century, he should not only raise the height and armour the front of sea embankment, but also improve the effectiveness of drainage system.

9.3. Flood damage in Heysham-Morecambe region

Heysham and Morecambe lie on the east coast of Morecambe Bay, facing westerly to the mouth of the Bay (Fig. 7.2.). Heysham combines residential and industrial districts, in which the harbour and the nuclear power station are two most important installations in terms of their support to the regional industries. Morecambe is a rather residential district with a well-known sea-side resort attracting a great number of tourists. These two districts lie on the low-hilly coastal area and are physically linked and under one district council.

The majority of the old towns are built on the land over 8 m O.D. With the rapid increase in population since the 1940s (Fig. 9.3.), the urban areas were expanded and partly extended on to the lowlying lands around Morecambe (Fig. 9.4.) which is now subject to flood.

In order to work out the altitude in detail of the area, a three-dimensional digital elevation model (Leenaers and Okx, 1989) is established in a SUN machine by combining the contours from the 1:25,000 O.S. maps and the spot heights from the 1 km square O.S. maps. This model can be used to present the surface relief of the area (Fig. 9.5.) and to produce a contour map with one metre intervals (Fig. 9.6.). From which, the 5 and 8 metre contours are transformed into the GIS databases, which include landuse type, contours, and MHW mark (Fig. 9.4.).

A storm surge attack to the Harbour and the Power Station

By the year 2050 for example, the MHWST at Heysham Head could reach a height of 5.06 m O.D. and the HAT, 6.16 m O.D. (the Scenario 2). The existing quays of the Heysham Harbour are around 8 m O.D. in height. The ground floor of the Nuclear Power Station is only about 10 m O.D. Providing that a 1.7 extra height of water from a 1/100 storm surge (Tooley, 1989; Graff, 1981) is added upon a high spring tide (MHWST, for example), and providing a 1 m height of waves driven by the westerly wind which could be created by a stormy meteorological condition, the highest water level would reach a height of 7.8 - 8.9 m O.D. If this assumed condition occur, the facilities in the Harbour and the Nuclear Power Station would be under attack of sea water. This condition would occur in around 2050-2060 if sea level rises as Scenario 2, or in around 2080-2100 if sea level rises as Scenario 1.

During such attacks, the facilities in the Harbour and the goods piled upon the quays and stored in wharves nearby would be seriously damaged. The cost in maintenance and the consequent interruption of harbour services would also be great. This sort of attack to the Nuclear Power Station could damage the facilities and could potentially lead to a release of the radio-active materials which would, in a long term, consequently damage the coastal inhabitants and animals along the coasts around Morecambe Bay in particular.

A storm surge attack to the residential area

Under the same situation, an attack from a combination of storm surge, high spring tide and sea wave could concentrate on the urban area along the water front from Sandylands of Heysham to Poulton of Morecambe (Fig. 9.7.). The height of the concrete sea wall along this sea front was at 6.2 - 7.4 m O.D. (data from Lancaster City Council). To maintain the sea front resort, a new development in the Central Promenade area is being planed. A new wave reflection wall is expected to built upon the former sea wall with a constant height of crest at 8.5 m O.D. Stones and boulders will also be filled on the top of the existing beach in front of the former sea wall.

If sea level rises as Scenario 1 (see Table 8.1.), this area could be safe during the next century, except should an extreme water level higher than the 1977 one occur. If sea level rises as Scenario 2, this area will be under threat of sea water overtopping and flooding in the last quarter of the next century. In the first instance, this attack would be likely to overtop the sea walls and damage the Marine Road by deposition of sands, gravels, and debris. Such attack could also temporary stop the service of the railway station by damaging the facilities such as signal systems. Secondly, the wave attack would damage the urban facilities such as the Fairground, Shops, Library, and the Swimming Stadium, which are located within the wards of Harbour, Poulton, and Victoria. Thirdly, this attack could also induce a flood through the ward, Harbour, in where the ground level is around 5-6 m O.D. Consequently, the flood water could run into the lowlying land (4.5 - 5.5 m

O.D.) behind Heysham and Morecambe (Fig. 9.4.), in where the new houses and two large caravan parks would be damaged.

This sort of damage induced by the rising sea-level would be likely to happen at Fleetwood and Barrow-Furness, and Southend, Tilbury, Erith and other urban areas and industrial areas along the Thames. A similar event did happen during the 1953 disaster near the Wantsum Channel. It was described (Coleman and Lukehurst, 1967) that two breaches of 700 and 800 yards respectively were made in the northern sea wall and the railway was put out of action for four months. Many bridges, sluices, dams and gateposts were undermined or blocked by flood debris.

A flood from breaching the embankments on the Lune

In the lower reaches of the River Lune around Lancaster, a flood level would reach a height of 7.1 - 8.1 m O.D. by the year 2050, if an extra 1.7 height of water level induced by a 1/100 storm surge (Tooley, 1989; Graff, 1981) being added upon a high spring tide level (5.4 m O.D., MHWST; 6.4 m O.D. HAT). Furthermore, such a high water level, if it happens during a spring season (from October to January, see Table 7.5.) as usual, could be enhanced by the high fresh water flow which comes from the Lune catchment. This event, if it occurs, could definitely induce a serious flood. Sea water could breach or overtop the earth embankments along the lower reaches of the Lune, running over the Oxcliffe Marsh into the new housing area at White Lund, or over Peggy Marsh into the farm lands behind Heysham (Fig. 9.7.).

After the flood, sea water would be difficult to drain out from the farm lands due to the ground surface is slightly lower than the surroundings. Waterlogging for a rather long time would therefore be likely.

9.4. Storm surge attack on a lowland community: a case study from Canvey Island

Canvey Island lies on the north side of the Thames Estuary about 48 km from London. The island covers about 15.7 km^2 in area, and is separated from the mainland by a tidal creek and entirely enclosed by a high sea wall. Seen from the mainland at South Benfleet, the island appears to comprise little more than flat featureless marshland stretching away to the distant sea wall (Cracknell, 1959). As one crosses the island towards the south-eastern part, however, a very different landscape is revealed, a curious half-urban, half-rural, assortment of dwellings sprawling in haphazard fashion over a wide area (Cracknell, 1959). Over 35 thousand people now (the 1981 census) live in this rapidly growing urban area (Fig. 9.8.), which barely eighty years ago was inhabited by only a few farmers, fishmen and their families (Cracknell, 1959).

History of the Island

Several distinct communities have dwelt on the island since man first settled there (Cracknell, 1959). The salt-maker's community during Roman

Times was followed by the shepherds' community during the centuries between the mid-Roman period and the Norman Conquest. During the 16th century when the Netherlandish community came, a sea wall was built in order to protect the agricultural activities and the settlements from sea inundation. During the 17th century, the English community gradually replaced the Dutch community due to the dramatic change in political climate. The English community had maintained the workshops, roadways and the sea walls. The sea walls were repaired and strengthened during the opening years of the 19th century due to the breaching of the sea walls becoming more serious and more frequent. Since the decline in agricultural activities which were seriously affected by the importation of cheap wheat from the New World during the late 19th century, a new community was primarily settled at the island where City people spent their summer holidays and week-ends in the early 20th century, but gradually the number of permanent residents increased and the facilities provided for them improved.

During the 20th century, the population increased rapidly, even after the 1953 disaster (Fig. 9.9.). During the days of January 31 - February 1, 1953, when a surge attacked Canvey Island, the major walls along the sea front with the Thames held, and the flooding took place mainly over the lower and weaker walls along the tidal creeks (Steers, 1953). About 40 breaches varying in width from 10 to 200 ft were made in the sea defence along the creeks (Robinson, 1953). As a result, fifty-eight people lost their lives and thousands of houses were seriously damaged (Cracknell, 1959). It was also reported that the parts of Canvey Island which suffered most severely from the floods were (a) the Newlands in which the Coryton Oil Refinery was flooded after a break in the sea wall never previously breached (Robinson, 1953), and (b) the marshes on the eastern side where flood water was as much as twenty feet (about 6 m) deep in places.

After the 1953 disaster, however, the island attracted even more investors such as the British Gas and other manufacturers, and as well as more people moving into the island. Such attraction might be partly of the land which is much cheaper and flatter than those surrounding the island, and partly the protection of the improved sea defence which was intensively repaired and raised up to a higher standard after the 1953 disaster. A study of the records of the Commissioners of Sewers for the Thames Estuary marshes over the past three hundred years shows that serious flooding occurred with remarkable regularity every fifty years or so; this may well be explained, at least in part, by the complacency which so often set in after a period of intensive work on the walls following a serious flood (Cracknell, 1959).

Current situation

During the last 80 years, a dense urban area has emerged in the eastern half of Canvey Island, and oil refineries and manufactures have been built on the south-western part of the island, whilst cattle pastures still remain in the north-western part (Fig. 9.8.). The current ground level varies from 0.9 to 2.3 m O.D. and the 2 m contour is drawn (Fig. 9.10.) by a contouring programme using the spot heights which are collected from the one km square sheets at the Ordnance Survey. The ground altitude of the urban district on the southeastern part of the Island is currently about 0.5 m lower than that of the agricultural land on the northwestern part of the Island.

During the current investigation, it is known that the sea wall along the northeast, east and south coasts of the island is a type of mainly soil-filled embankment with stone or concrete armoured on the front and a concrete wave-reflection wall on the top (Photos 13-18). The crest of the wave-reflection wall is of 6.2 - 6.9 m O.D. (data from Castle Point District Council). These heights are confirmed by the current study (Table 9.1.). However, along the west and north-west coasts, i.e. along the creeks, the embankment is only soil-filled without concrete ramp and stone armour . The crest of the soil embankment without armour is around 5.0 - 5.5 m O.D. (from the 1:10,000 O.S. maps, 1982-1985).

Table 9.1. Heights of the sea embankment (southwest sector) in Canvey Island measured by the current study (August 1990)

Coordinates	Height (m O.D.)	Description
TQ 7725 8218	6.913	on the top of the concrete wall
7721 8227	6.942	same as above
7718 8230	6.906	same as above
7718 8230	5.315	on the top of the soil embankment
7710 8251	6.843	on the top of the concrete wall
7701 8270	6.686	same as above
7688 8286	6.518	same as above
7671 8305	6.401	same as above
7645 8325	6.386	same as above
7625 8326	5.348	on the top of the soil embankment
7625 8326	6.216	on the top of the concrete wall

If sea level rises as Scenario 1 during the next century, water level of the MHWST could reach a height of 3.23 m O.D. (at 2050) or 3.68 m O.D. (at 2100)(Table 8.1., referring to Southend). Also, the HAT level could rise up to 3.93 m O.D. (at 2050) or 4.38 m O.D. (at 2100). If an extra height of 2 m from a 1/100 surge being added upon a high spring tide, breaching and overtopping the existing soil embankments would be very likely by the year 2050 or a little earlier.

If sea level rises as Scenario 2, the HAT (Table 8.1.) could overtop the soil embankment before the year 2100. An extra 2 m height adding upon a high spring tide (MHWST for example) could be able to breach the concrete reflection wall before the end of the next century. Once the breaching occurs, the properties within the island would be undoubtedly seriously damaged.

Damages in the urban area

At first, once sea water breaches or overtops the sea embankment, sea water would fall down from a height of about 6.5 m O.D. to the ground which is 4.5 or 5.0 m lower, as a water fall. Such suddenly falling of sea water could create a great power to erode and destroy the properties and installations nearby, as well as the embankment itself. A great amount of debris and sands could rush in and be deposited over the ground of the Island. The damage would be much more serious than those in Heysham and Morecambe, and those in Towyn (Englefield et al., 1990).

Secondly, because the Island is entirely enclosed and the ground level is lower than the MHWST, flood water in the island would be much more difficult to drain out, particularly when sea water only breaches the soil embankment along the creeks. Thus, the inundation could last over a few days or even longer. The structure of houses, domestic furniture and facilities, and any other public facilities would be seriously damaged. Public services could be stopped for an even longer time.

Thirdly, it is no doubt that such flooding could kill people, especially the old people and children. In Canvey Island, there is currently only one road (the A13) that can be used for people to escape and for evacuation. The efficiency of evacuation through this road would be partly a key function to the safety of the people. In the other words, there will be more casualties occurring in case of an interruption of the road when the island is flooded.

Fourthly, even if sea water breaches the soil embankments along the Benfleet Creek as it did in 1953, sea water could rush south-eastward into the urban area (Fig. 9.10.). Therefore, sea water could flood over the current escape road (the A13), and run into the urban area afterwards. It means there would be no way for the local residents to escape. Hence, even having a car is no advantage, under such circumstances.

Damage in the oil industries

Indeed, the sea defence in front of the oil refinery and the oil storage are in a highly effective standard with its crest at a height of 6.9 - 6.2 m O.D.

(Table 9.1.). They are the type of the Exposed Estuary Wall protecting a built-up area (Thorn, 1960) and can withstand wave attack. However in case sea water overtops the sea defence, the facilities of the oil refineries may be seriously destroyed, because of the great power of the flood water. Providing that sea water does not breach or overtop them but that the soil embankment along the north shore of the Island is breached, sea water could still rush southwards and flood the facilities of the oil refineries (Fig. 9.10.).

As a result of the flooding, oil refinery equipment and pipelines could be damaged. It would consequently induce a release of the oil and other chemical materials which could contaminate the urban area of the Island in particular, as well as the Thames Estuary and the southern North Sea. Similar damage would be also likely in the heavy industrial areas along the Thames lowlands (Figs. 8.8., 8.9. and 8.10.) if a flood occurs.

A decision difficult to make

In Canvey Island, the sea defence system only protects an area of 15.7 km^2, about 35,000 residents and a oil refinery plant and some small factories. If the current sea defence system is not raised or improved to cope with the rising sea-level, the threat of sea flooding would lead the residents migrating to inland, and also force insurance companies to increase the insurance premium for the properties. Such tendency could in turn reduce the values of properties and the land, as well as the economic potential of the island.

In order to stop this tendency and maintain the economic potential of the island, the sea defence should be raised in height and armoured on the seaward front of the soil embankment. This improvement should not be later than the year 2050 if sea level rises as Scenario 2. However, such engineering work must be very expensive. Raising money for this work would be one of the difficulties. On the other hand, would the benefit of such improvement be higher than the cost ? Making a decision whether or not to improve the sea defence would require consideration of factors in economy, politics, and also psychology.

9.5. Summary

Three pilot areas, Skelwith Pool, Heysham and Morecambe, and Canvey Island, have been investigated in detail to identify the likely damage from a sea flood on different landuse types. It is suggested that damage to agricultural land could include sea water inundation which can directly damage the growing crops, livestock, farming facilities and result in the loss of human life. Providing the sea defence level being raised sometimes during the next century, the rising sea-level could still raise the ground water table which can cause drainage difficulties and damage the growing crops. In addition, raising sea embankments could cause even more difficulty to drain the sea water out after a flood, and consequently induce a longer time of inundation or waterlogging.

Damages to urban areas and industrial estates would be various. Although there are usually sea defence systems at a relatively high level protecting the urban and industrial areas, waves and surge tides could still be able to attack the people and properties in the areas. Once sea water overtops the high level defence, high velocity inundation could seriously damage the properties nearby and the sea defence itself. Along the water front of Heysham Head, Morecambe Bay, and the lower reaches of the Thames Estuary, there are large numbers of expensive industrial installation, including power stations, oil refineries, dockyards, sewage work, chemical plants and factories. Population in the areas are also very dense. In addition, there are many national offices, archives, historic buildings, on the south bank of London in particular. Therefore, it is clear that the loss from a sea flooding over these areas would be incalculable.

It is difficult to define a hazard in human terms, but the usual basis for defining the impacts of a natural hazard is in terms of economic loss and loss of life (Doornkamp, 1990a). This sort of work, as well as the cost-benefit estimation, could only taken as a model, and requires detail assessment such as the current studies for the three pilot areas.

CHAPTER X

CONCLUSION

10.1. A Summary of the Study

The current studies are summarised under four headings: Flandrian sea-level history, Future sea-level rises, Coastal responses to the changing sea-level and Likely marine inundation and damage.

10.1.1. Flandrian sea-level history

On the basis of the current stratigraphic survey, pollen and diatom analyses and radiocarbon dating, the Flandrian sea-level history of Morecambe Bay has been illustrated. Some points of view from the studies can be described as follows.

(1) The relationship between a regressive overlap and a movement in sea level has been discussed. It is indicated that a regressive overlap does not necessarily mean a fall in sea level. Pollen and diatom analyses from some of the saltmarsh sequences have suggested that a rising sea-level at a rate of 0 - 4 mm/year could sometimes encourage a vertical accretion in saltmarshes and not always result in lateral retreating of saltmarshes. In other words, some of the

regressive overlaps are associated with a slowly rising sea-level.

(2) Shennan's inductive model (1982) has been employed to establish positive and negative tendencies in sea level during the study. In Morecambe Bay, there are only 28 dates throughout the last 9000 years. The number of dates in Morecambe Bay is clearly insufficient. Thus, the current study has to base on both the tendency model and the stratigraphic sequences, in order to reconstruct a reliable sea-level history.

(3) For sea-level study, Tooley's three criteria (Tooley, 1978a, 1985a) are reasonablely applicable. For comparison to a relatively large area, such as Morecambe Bay, variation in tidal range within the area should not be ignored. However, this study suggests that the deglaciation in the Lake District has caused a local isostatic tilting - an uplift in the northern part of Morecambe Bay including the Leven and Kent estuaries and their catchments, and subsidence in the central and southern parts of the Bay. There are seven sea-level index points collected from the basal peat which underwent the subsidence. Other index points come mainly from the northern part of the Bay which has undergone an uplift process. Therefore, the seven index points from the basal peat should not be applied with those from the northern part of the Bay together to reconstruct the spatial changes in Flandrian sea level.

(4) Before calculating the rates of sea-level change for Morecambe Bay, local factors of regional and local isostatic components and variations of tidal amplitude through time have been considered. The amplitudes of these factors

have also been hypothesised.

(5) On the basis of the present study, the Flandrian sea-level history of Morecambe Bay can be summarised as follows. **A.** During the beginning of the Flandrian, the bed of the Bay was rather flat due to late and early post-glacial lake and alluvial deposition. **B.** In the late 9th millennium and the 8th millennium, as a result of a rise in sea level from -20 to -17 m O.D., only the bottom of the valleys was inundated. Saltmarshes were deposited as part of the basal peat formation. Due to that the sea bed within the Bay was broad and flat, tidal range was presumably smaller than the present. **C.** By the end of the 8th millennium and the early 7th millennium, sea level rose rapidly at a rate over 30 mm/year (Tooley, 1978a) and the Bay was entirely inundated. Due to the sea water being relatively deep and the coasts being restricted by hills of solid rock, in the Leven and Kent estuaries in particular, tidal range within the estuaries was greatly enhanced and was presumably larger than the present. The area inundated at that time was much more extensive and further up-estuary than the present. Consequently, saltmarshes had to grow around the heads of the estuaries, and organic clay, called gyttja deposited in some sheltered sites.
D. During the period from the 7th millennium to the 4th millennium, sea level rose and fluctuated and sometimes fell slightly. The rates of sea-level movement vary from -2.0 to 8.0 mm/year and cause a series of sedimentary sequences alternating between marine clastic sediments and brackish saltmarshes. **E.** Sea-level history during the last 3500 years is not clear due to lack of evidence.

It could be assumed however that the magnitude in sea-level change was small.

F. The critical rate allowing a transgressive overlap to form seems varying from place to place and depending on the morphology and sediment supply in the site. It is suggested that the range of the critical rate might vary from 3 to 5 mm/yr, according the evidence in Skelwith Pool.

10.1.2. Future sea-level rises

The likely rises in sea level induced by global warming in the next century have been estimated by some authors. However, various uncertainties have been involved with these estimations. For this reason, two sea-level scenarios have been employed critically to the present study. Of which, Scenario 1 was borrowed from the best guess scenario of the business-as-usual scenarios in the IPCC report (Warrick and Oerlemans, 1990). Scenario 2 was applied from the average of the Hoffman's (1984) Mid-range estimates. By considering the local factors of glacial isostatic uplift in Morecambe Bay and subsidence in the Thames Estuary, an assessment of the likely sea-level rises in the next century is made, and two scenarios for the two areas studied are given (Tables 7.8. and 7.13.).

As a deepening in sea water could shorten the return period of a surge tide, the return period of abnormally high water levels in the two areas are assessed. It is predicted that the 1977 flood level with a 1.7 m extra height could occur around the year 2050 or within the next century in Morecambe Bay, and that a 2 m extra height of storm surge level adding upon a high spring tide could occur during the same time in the Thames Estuary.

By considering the local hydrological features and the intertidal morphology in both areas studied, variation in tidal amplitude from one location to another has been analyzed. The projected high water levels, such as the MHWST and HAT, are also calculated for the two areas.

10.1.3. Coastal response to the changing sea-level

The physical impacts of projected sea-level rises in the two areas have been assessed in terms of the coastal response to the changing sea-level. This includes responses of hydrological condition, coastal sedimentation, coastlines and saltmarshes. Several points of view on these responses have been illustrated as follows.

(1) The tidal system and sedimentary pattern in both areas may not be considerably changed, as sea-level rises as Scenario 1.

(2) A rising sea-level could enhance the tidal amplitude upstream in the Thames Estuary as it used to be. However, the rising sea-level could not increase tidal amplitude in the northern and southeastern parts of Morecambe Bay. It is because a rising sea-level could inundate more formerly dried-out areas and could change the geometry and the sea-bed morphology of the Bay, so that low waters could rise faster than the high waters. As a result, in the northern and southeastern parts of the Bay, the tidal amplitude could be reduced

slightly but the intertidal zone could become wider. Hence, in these parts of coasts, wave energy could be dissipated more effectively.

(3) In the Thames Estuary, intertidal sediments will be more moveable and more frequently recycled. Erosion on the Chalk formation along the coast of North Kent will be more active and could produce more suspended sediments which could be carried into the Estuary. These and other suspended sediments would be deposited further upstream from the Mud Reaches.

(4) In Morecambe Bay, more fine-grade sediments would tend to deposit in the upper intertidal zone, especially in northern and southeastern parts of the Bay.

(5) If sea level rises as Scenario 1, the saltmarshes in Morecambe Bay could accrete much faster as some of fine-grade sediments will deposit over the marsh surface. But the erosion along the seaward edge of the marshes would still continue. If sea level rises as Scenario 2, accretion of the existing saltmarshes may not be able to keep pace with the rising sea-level. Therefore the saltmarshes would be either eroded seriously or overlaid by marine clastic sediments.

(6) Some coastlines around Morecambe Bay would retreat if sea level rises as Scenario 2. Wave attack to the sea embankments would become more serious, and erosion at the seaward front of the embankments would occur.

10.1.4. Likely marine inundation and damage

The landuse type of the coastal lowlands currently protected by sea defence has been investigated. The nature of the existing sea defence has also been assessed, in terms of their effectiveness preventing the future high water levels.

(1) In order to identify these impacts, a zoning of the likely flood-hazard lands is therefore carried out in the present study. Such zoning includes two major tasks. At first, it is to work out what is the likely flood-hazard land from the future rising sea-level, where they are, how extensive this sort of land will be, and what type of landuse has existed on these land. In order to achieve the first task, geographical information systems of the two areas have been established, including data of altitude, landuse type, population, and communication networks. The second task of the zoning is to identify the likely hazards which would occur on the lowlands. Three small pilot areas were therefore selected to complete the task.

(2) The two lowland areas have been assessed in terms of their ground altitude. It is indicated that in Morecambe Bay there are land of 124.6 km^2 below the +5 m contour, and 346.6 km^2 below the +10 m contour. In the Thames Estuary, there are land of 513.6 km^2 below the +5 m contour and of 291.5 km^2 between the +5 m and the +10 m contours. These lands would be directly damaged from sea flooding or indirectly affected from the back-flows of fresh water in the next century. These lands are currently used for agricultural

purposes, industrial estates, urban and residential areas and communication networks.

(3) The existing sea defence systems in the two areas may still be effective during the early decades of the next century, would be breached around the year 2050, and will be ineffective to protect the lowlands during the second half of the next century, unless they are raised and reinforced before the disasters happen.

(4) The studies in the three pilot areas have indicated that, in general, the standard of sea defence for agricultural lands is relatively lower than that for industrial and urban areas. For agricultural lands, major damages from a rising sea-level would include direct flooding and damaging the growing crops, contamination of the soil, a raising in ground-water table which could cause waterlogging, and difficulty in drainage. For industrial estates, sea flooding could damage the equipment and facilities, stop production, release chemical materials and radioactive materials (at Heysham for instance), and contaminate the adjacent areas (Morecambe Bay and the northeast part of Irish Sea; the Thames Estuary and the southern North Sea). For the urban and residential areas, damage could come from wave attacks which would happen along the water front of the areas, and could be caused by flood water which will come from the breaching of the weak sections of the sea embankments. Such wave attack and flooding could drown people, damage properties, interrupt transportation, and stop temporarily the public services and businesses.

10.2. Further Study Needed

On the basis of the present study, several aspects of study seem to be urgently needed in the near future. At first, more intensive investigation of the palaeo-geography in coastal areas, qualifying and quantifying sea-level and coastline data in particular, should be carried out. In Morecambe Bay for example, an intensive stratigraphic survey should be carried out along the Leven and Kent estuaries and the Pilling area, in order to confirm the results of the present study.

Secondly, refined numerical modelling to simulate the hydrological and sedimentary responses to the changing sea-level constrained by empirical data would produce significant results. Intensive and comparative investigations of the current hydrological and sedimentary processes would be valuable.

Thirdly, altitudinal and landuse databases with higher resolution would be critical for future study of the impacts of sea-level rises. Assessment should be based not only on the physical units (i.e. a bay and an estuary), but also on administrative units (at district level, for instance). Collaboration should be made not only with national and international academic centres (universities, colleges, institutes and laboratories), but also with local authorities (local councils and water authorities) and organisations (environmental protection boards, industrial associations, financial agencies, insurance companies and solicitors).

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